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Quantification and valorisation of agricultural bioresource residues in England

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Quantification and valorisation of agricultural bioresource residues in England.

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Abstract

This research investigates the current utilization of livestock waste arising from manures, slurries and crop-based feedstocks via Anaerobic Digestion (AD) in England with a focus on the quantification of the technical biomass resource potential and the economics. The technical potential refers to slurries and manures that are stored and not immediately spread to land, hence available to use in AD systems. A GIS tool has been developed that evaluates the availability of livestock waste and compares it with the actual utilisation of manures by operational biogas plants to quantify the latent biogas potential from unused livestock. The GIS tool has been applied to a region in the South West of England in order to analyse the impact of policies setting out minimum targets of 25 % and 50 % utilization of the biomass technical potential in AD plants. An Excel-based biogas calculator has been developed that enables economic assessment of on farm AD projects. Operational and financial data has been gathered via interviews and questionnaire from eight case studies representative of on farm biogas installations utilizing agricultural feedstocks. This dataset has been used to evaluate the predictions of the biogas calculator and estimate the four parameters of the underlying first order kinetic model via non-linear curve fitting in Matlab. Across England there are approximately 29 million tonnes of manures and slurries per annum that could be used to feed anaerobic digestion systems. Only about 5 % of this potential is utilized. An additional 32.7M GJ year^{-1} of renewable energy could be generated as biogas if the unutilised 95 % of agri-biosolids was used as feedstock in AD systems. In the region examined 40 additional AD plants with capacities ranging between 100 to 198 kW_{el} and 131 additional AD plants with capacities ranging between 61 to 190 kW_{el} are needed if the policy targets of utilizing respectively 25 % and 50 % of total biomass potential from livestock are to be met. This confirms that manures and slurries are underutilised substrates for anaerobic digestion and that there is still considerable potential for further development in England. This study also lays the foundation for the creation of a fully integrated biomass resources management tool.

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I am grateful to my family and my extraordinary friends in Bath, Ioanna, Olivia, Laura, Ernesto, Naomi, Marios and others, who have helped me to get through the most difficult times during my PhD. Luz, you made my days in the office delightful and joyful. You gave me the motivation and the energy to keep going. I think I would have not gone so far if it was not for all of you. You are special and deserve all credits.

Table of contents

List of Tables

List of Figures

Abbreviations

AD	Anaerobic digestion
ADM1	Anaerobic Digestion Model 1
ALCA	Attributional life cycle assessment
AP	Acidification potential
BD	Biodegradability
BMP	Bio-methane potential
BSI	British Standards Institution
Capex	Capital expenditure
CHP	Combined heat and power
CLCA	Consequential life cycle assessment
COD	Chemical oxygen demand
CSTR	Continuous stirred-tank reactor
DLUC	Direct land use change
DS	Dry solids
DWC	Delactose whey concentrate
EP	Eutrophication potential
FIT	Feed-in-tariff
FYM	Farm yard manure
GHG	Greenhouse gas
GIS	Geographical information system
HRT	Hydraulic retention time
ILUC	Indirect land use change
IRR	Internal rate of return
JAS	June agricultural survey
LA	Local authority
LCA	Life cycle assessment
LCM	Land cover map
LCOE	Levelized cost of energy
LHV	Low heating value
MBR	Membrane bioreactor
MOP	Muriate of Potash
NMC	Nitrogen mineralisation capacity
NPK	Nitrogen, Phosphorous, Potassium
NPV	Net present value
NVZs	Nitrogen vulnerable zones
OLR	Organic load rate
Opex	Operational expenditure
PAS	Publicly-available specification
PEIO	Primary energy input output
PRR	Partition release recovery
RED	Renewable Energy Directive
RHI	Renewable heat incentive
SBR	Sequencing batch reactors
STP	Standard temperature and pressure
TKN	Total Kjeldahl nitrogen
TS	Total solids

TSP	Triple superphosphate
UASB	Upflow anaerobic sludge blanket reactor
VFA	Volatile fatty acids
VS	Volatile solids
WRAP	Waste & resources action programme
WWTWs	Wastewater treatment works

Nomenclature

Symbol	**Name**	**Units**
$\%CH_4$	Percent of methane in biogas	%
$\%Losses\_CH_4$	Methane losses from the biogas plant	%
A	Total area of the digester (roof, floor and walls)	m^2
ABT	Annual Biogas throughput	$m^3\ y^{-1}$
$APPE$	Annual potential production of energy from biomass	$MJ\ y^{-1}$
$APPE_{Plant}$	Annual potential production of energy from the biogas plant	$MJ\ y^{-1}$
$APPM$	Annual potential production of methane from biomass	$m^3\ CH_4\ y^{-1}$
$APPM_{Plant}$	Annual potential production of methane from the biogas plant	$m^3\ CH_4\ y^{-1}$
$arable1_i$	Agricultural land area according to the June agricultural survey by DEFRA in local authority i	ha
$arable2_i$	Agricultural land area according to the Land Cover Map of the UK in local authority i	ha
BHT	Biogas hourly throughput	$m^3\ h^{-1}$
BMP	Bio-methane potential in a CSTR digester after a time equivalent to HRT, STP	$L\ CH_4\ kg\ VS^{-1}$
$BMP(t)$	Cumulative bio-methane potential, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_0	Ultimate bio-methane potential, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_0^i	Ultimate bio-methane potential of component i in the feedstock mix, STP	$L\ CH_4\ kg\ VS^{-1}$
$BMP_o^{crops/waste}$	Ultimate bio-methane potential of the crop component in the feedstock mix, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_o^{manure}	Ultimate bio-methane potential of the manure component in the feedstock mix, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_o^{Mix}	Ultimate bio-methane potential of the feedstock mix, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_{plant}	Calculated bio-methane potential of the biogas plant	$L\ CH_4\ kg\ VS^{-1}$

$BMP_{Storage}$	Bio-methane potential in the storage tank after a time equivalent to HRT, STP	$L\ CH_4\ kg\ VS^{-1}$
BMP_{Th}	Theoretical bio-methane potential (Buswell), STP	$L\ CH_4\ kg\ VS^{-1}$
$BMP_{Th,COD}$	Theoretical bio-methane potential (Buswell), STP	$L\ CH_4\ kg\ COD^{-1}$
BMP_{total}	Total bio-methane potential after storage, STP	$L\ CH_4\ kg\ VS^{-1}$
Capacity	Daily loading rate of the solids feeder	$m^3\ d^{-1}$
Capex	Capital expenditure	£
COD_{Th}	Chemical oxygen demand	$g\ COD\ g\ VS^{-1}$
c_p	Specific heat capacity of the feeding stream	$kJ\ kg^{-1}\ °C^{-1}$
D	Dilution	wet tonne y^{-1}
d	pipe diameter	m
$d_{i,j}$	Distance between demand node i and potential facility location j	m
DS	Dry solids	%
DS_{in}	Dry solids content in the feed	%
$DS_{liquour}$	Dry solids content in the dilution stream	%
DS_{target}	Dry solids content to achieve in the digester	%
e	Euler's number, 2.718	-
E_{kWh}	Electricity produced by the biogas plant in one year	$kWh\ y^{-1}$
$E_{kWh,parasitic}$	Electricity needed by the biogas plant in one year	$kWh\ y^{-1}$
$E_{kWh,mixing}$	Electricity required for mixing in one year	$kWh\ y^{-1}$
$E_{kWh,pumping}$	Electricity required for mixing in one year	$kWh\ y^{-1}$
EPL	Electric parasitic load	%
f	friction factor	-
$FV_{digestate}$	Financial value of digestate as bio-fertiliser	$£\ kg\ N^{-1}$
FV_{manure}	Financial value of manures as bio-fertilisers	$£\ kg\ N^{-1}$
g	gravity constant, 9.81	$m\ s^{-2}$
h_i	Demand at node i	wet tonne y^{-1}
HPL	Heat parasitic load	%

HRT	Hydraulic residence time in the main digester	d^{-1}
$HRT_{storage}$	Hydraulic residence time in the storage tank	d^{-1}
i	Index of demand node	-
j	Index of potential facility location	-
k	First order kinetic constant	d^{-1}
k_{crops}	First order kinetics rate of the crop component in the feedstock mix	d^{-1}
K_f	Rate constant for rapidly degradable substrate	d^{-1}
K_I	Inhibition constant	$g\ L^{-1}$
K_L	Rate constant for slowly degradable substrate	d^{-1}
k_{manure}	First order kinetics rate of the manure component in the feedstock mix	d^{-1}
k_{Mix}	First order kinetics rate of the feedstock mix	d^{-1}
K_S	Half saturation coefficient	$g\ L^{-1}$
$k^s(T)$	First order linear reaction rate	d^{-1}
K_X	Contois kinetic constant	$g\ L^{-1}$
L	pipe length	m
LHV_{CH4}	Low heating value of methane	$MJ\ m^{-3}$
n	Number of potential facility locations	-
N	number of data points for RMSE calculations	-
NFV	Net Fertiliser Value	£ y^{-1}
n_H	Haldane constant	-
n_i	Total number of centroids within the local authority	-
Op_hr	Operational hours of the CHP unit	h
$Opex$	Operational expenditure	£ y^{-1}
p	A subset of n potential facility locations	-
p_1, p_2	Pressures in the head space in tank 1 and tank 2	Pa
$P_{capacity}$	Capacity of the feeding pump	kW
P_N	Price of N fertiliser	£ kg N^{-1}
q_{feed}	Energy needed as heat to raise the influent temperature to the digester temperature	kWh
Q_i	Flowrate of feeding stream in month i	wet tonne y^{-1}

Q_{in}	Total annual wet tonne of feedstock utilized	wet tonne y^{-1}
q	Total Energy needed as heat to keep the temperature in the digester constant	kWh
q_{losses}	Energy needed as heat to compensate heat losses through digester walls, roof and floor.	kWh
q_{total}	Total heat generated via biogas combustion in the CHP unit	kWh
q_{wasted}	heat wasted that cannot be utilized in the CHP unit	kWh
$RAN_{digestate}$	Readily available nitrogen in digestate	g N L^{-1}
Re	Reynolds number	-
R_{max}	Maximum methane production rate, STP	L CH_4 kg VS^{-1} d^{-1}
$RMSE$	Root mean square error	-
S	Substrate concentration	g L^{-1}
S_0	Initial substrate concentration	g L^{-1}
$Savings_F$	Fertiliser savings	£ y^{-1}
t	Time	s
T	Temperature	°C
$T_{Air,i}$	Average temperature of air in month i	°C
TBP_{manure}	Technical biomass potential from manure	wet tonne y^{-1}
TBP_{straw}	Technical biomass potential from straw	tonne y^{-1}
$T_{Digester}$	Temperature in the digester	°C
TN_{feed}	Total nitrogen content in digestate	tonne N
Ton	Tonnage of crop silage ensiled at the biogas installation	wet tonne y^{-1}
TPC	Total physical cost of the biogas plant	£
U	Heat transfer coefficient	W °C^{-1} m^{-2}
v	fluid velocity	m s^{-1}
VS	Volatile solids	%
$\%VS_{manure}$	Fraction of volatile solids from the manure component in the feedstock mix	%
$\%VS_{crops/waste}$	Fraction of volatile solids from crops and waste in the feedstock mix	%
VS_{total}	Total volatile solids added to the main digester	tonne VS y^{-1}

VS_{total}^{i}	Total volatile solids from component i in feedstock mix added to the main digester	tonne VS y^{-1}
V_{Tank}	Volume of main digester	m^3
W_{CHP}	Electric power of the CHP unit	kW
W_{feed}	Power needed as heat to raise the influent temperature to the digester temperature	kW
W_{losses}	Power needed as heat to compensate heat losses through digester walls, roof and floor.	kW
W_{max}	Total power needed as heat to keep the temperature in the digester constant	kW
X	Microorganism concentration	g L^{-1}
x_i	variable estimated via model for RMSE calculations	-
X_j	Decision variable that is either 1 or 0	-
Y	Growth yield coefficient	-
y_i	variable as measured for RMSE calculations	-
$Y_{i,j}$	Decision variable that is either 1 or 0	-
z_1, z_2	Water levels in tank 1 and tank 2	m
ΔH	Total head	m
ΔP_{losses}	Energy losses due to friction in pipework	Pa m^{-1}
ΔT_1	Difference between the temperature of the feeding stream and the digester temperature	°C
$\Delta T_{2,max}$	Maximum temperature difference between the temperature in the digester and outdoor minimum air temperature	°C

Greek Symbols	**Name**	**Units**
α	Ratio of rapidly degradable substrate to total biodegradable substrate	-
η	Pump efficiency	-
η_{el}	Electric efficiency of the CHP unit	-
λ	Lag phase	d
μ	Viscosity of cattle slurry	Pa s
μ_m	Maximum specific growth rate	h^{-1}
ρ	Density of the feeding stream	kg m^{-3}

1. Introduction

Anaerobic digestion is a natural process mediated by anaerobic microorganisms occurring in oceans, lakes and soils. It converts organic carbon mainly into methane and carbon dioxide whilst mineralising organic nitrogen into ammonium. Anaerobic Digestion (AD) has been applied to the post-processing of primary and secondary sludges at Wastewater Treatment Works (WWTWs) for decades to stabilise waste sludge resulting from the biological treatment line.

This treatment ensures the stabilisation of sewage sludge due to the reduction of total COD (chemical oxygen demand) and volume, the removal of pathogens, and the production of a versatile fuel that is biogas. These beneficial aspects of AD have driven its widespread deployment at WWTWs. Its application provides an effective waste management solution to the hazard posed by primary municipal sludge and waste activated sludge.

The Renewable Energy Directive (RED) (European Parliament, 2009) aims to meet 20 % of the overall energy demand of the European Union by 2020, and 10 % of the total energy demand for transportation with renewable energy sources. This has been the major driver for the implementation of renewable energy technologies in Europe. Anaerobic digestion of bio-waste, along with other renewable energy resources like solar and wind, contributes towards meeting these targets. According to the Anaerobic Digestion & Bioresources Association policy report (ADBA, 2018), there are 449 AD biogas plants and 160 sewage sludge AD plants operational in the UK at April 2018 with a further 420 being planned.

Renewable energy production targets have prompted the launch of various financial support schemes across Europe aiming at rewarding the production of renewable energy. Financial subsidies have been essential to bridge the gap between the electricity production cost and market electricity prices. Since then, unit costs of solar and wind energy have decreased dramatically thanks to the exponential growth of these markets worldwide leading to the gradual reduction of financial subsidies.

Whilst solar and wind energy production can occur at grid parity under favourable climatic conditions, AD currently remains one of the most expensive renewable energy sources, requiring government support with little margin for capital expenditure reduction. In addition, the launch of financial incentives to produce biogas via anaerobic digestion has driven a shift in the value hierarchy from a waste treatment technology to a renewable energy technology, mainly delivering fuel for electricity, bio-methane injection or transportation.

In the UK, the Feed-In-Tariff (FIT) scheme (Ofgem, 2012) was introduced in April 2010 to subsidise electricity generation, by including a tariff guaranteed for the electricity exported to the electrical grid. The FITs have decreased gradually to a level that can barely ensure viability of electricity production from AD. The FIT scheme will close at the end of the first quarter of 2019. The Renewable Heat Incentive (RHI) scheme (Ofgem, 2016) followed in 2011, to support heat recovery from Combined heat and power (CHP), bio-methane production for injection to the gas grid, and liquid biogas transport fuel. AD delivers a variety of environmental services besides renewable energy production including:

- Digestate can be a higher value organic fertiliser.
- AD reduces total volume and total COD of sludge, as most of the initial COD ends up into methane.
- AD can reduce GHG emissions.
- Digestate improves soil quality by replenishing the organic fraction of the soil.
- Digestate can lead to crop yield improvement due to the higher content of mineralised nitrogen, hence leading to savings of manufactured fertiliser.
- Digestate has the potential to reduce risks of nutrient run-off and losses to surface waters, leading to water quality improvement.
- Pathogen removal.
- Odour abatement.

- Farming business diversification, development of rural areas through job creation, and local knowledge enhancement.
- Energy savings for farms, and other local consumers.
- AD provides a more stable baseload renewable energy source, essential for electricity grid stability, compared to solar and wind driven energy.

AD fulfils the principles of the circular economy (Stahel, 2016) as exemplified in Figure 1-1. The organic material in waste and crops is recycled back to land with different proportions of organic and inorganic compounds.

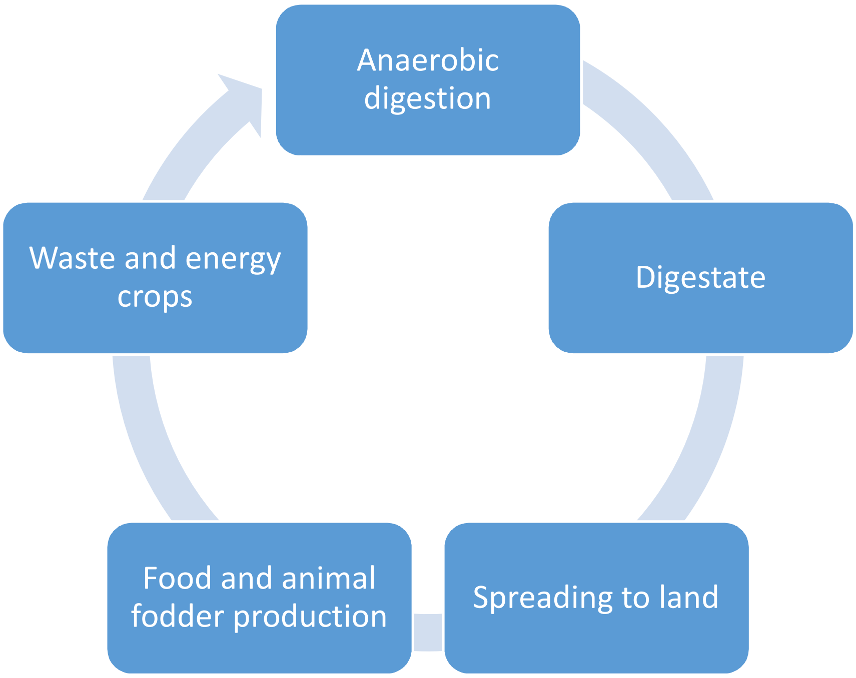


Figure 1-1: The schematic illustrates the circularity inherent in the nutrient recycling via digestate spreading after AD.

The treatment of bio-waste via anaerobic digestion complies with the principles of waste management set in the Waste Framework Directive (European Parliament, 2008). The waste hierarchy, shown in Figure 1-2, sets out the priorities in waste management starting from prevention, re-use, recycling, energy recovery and, as a last resort, disposal. AD sits between energy recovery and recycling.

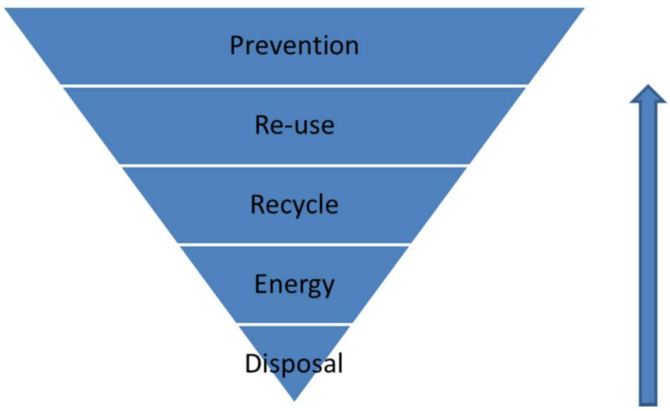


Figure 1-2: The waste hierarchy as defined by the Waste Framework Directive.

The major revenues from AD projects arise from heat, electricity, bio-methane sale, and gate fees where these are applicable. Gate fees are heavily dependent on local market conditions and competition. In England, commercial gate fees have steadily declined over the last years with a median value of £11 per tonne reported in the Waste & Resources Action Programme (WRAP) Gate Fees Report 2018 (WRAP, 2018). The median value rises to £26 per wet tonne charged to local authorities for waste disposal of municipal waste. Negative gate fees are possible where the plant operator pays a fee to receive waste.

Figure 1-3 illustrates the main outputs derived from anaerobic digestion of bio-waste, namely biogas and digestate. Almost the entire revenue from an AD plant derives from biogas while digestate does not generate any revenue. Despite the evidence gathered from field experiments showing the enhanced fertiliser value of organic manures (WRAP, 2016), digestate in most cases represents a disposal cost. The AD industry and the research community are striving to develop innovative and cost-effective technologies that can turn digestate into a valuable resource and marketable product. Contaminants in digestate, such as microplastics, can be a concern especially for food waste plants.

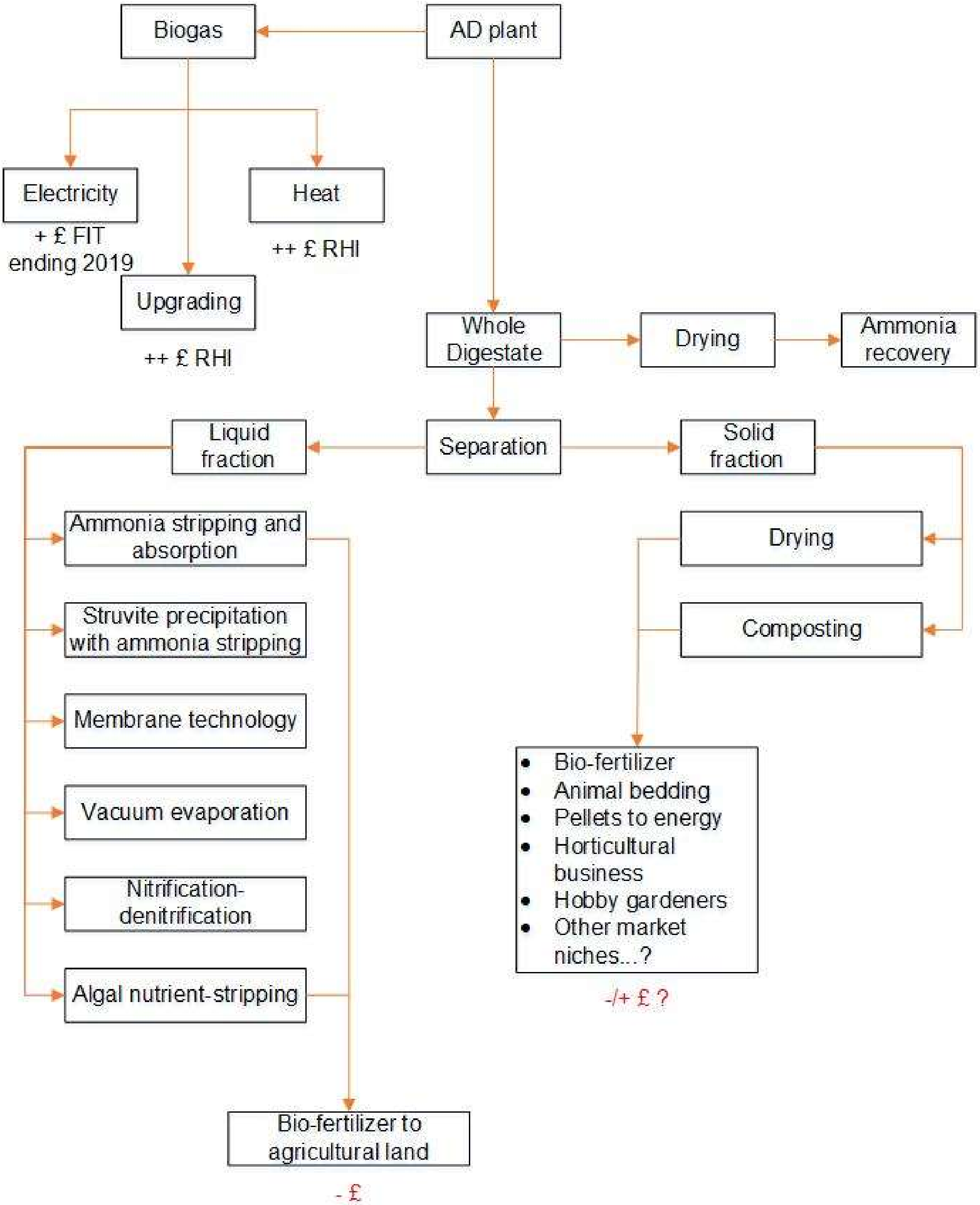


Figure 1-3: Revenue streams from biogas production along with various routes to enhance digestate value (Bolzonella et al., 2018).

Fertiliser savings from digestate spreading are difficult to budget due to the uncertainty associated with the prediction of the digestate fertiliser value and the actual plant uptake after spreading. This is due on one hand to the inconsistency of the bio-chemical characteristics of the digestate and, on the other hand, to the complexity of biochemical and hydrological processes occurring in soils that control nutrients fate. ADAS Ltd. has developed a freely available software, i.e. Manner NPK (Nicholson *et al.*, 2013), that can predict nutrient use efficiency and losses from fields after digestate applications as a guide for farmers.

Biogas plants produce large volumes of digestate that must be disposed of in compliance with environmental regulations and quality specifications (e.g., BSI PAS 110). Digestate originating from manure, energy crops and crop residues within a farm, or a group of farms, and recycled to agricultural land, is not subject to waste regulations and can therefore be directly applied.

Best management practices advise spreading digestate when crop nitrogen requirements are most needed (i.e., Spring / Summer), using efficient spreading methods (e.g. soil injection) to minimize ammonia emissions and reduce nitrate leaching to groundwater and surface waters. Best practices could soon become a requirement for digestate produced via AD including enclosing manure and slurry stores by 2027 (Defra, 2018a).

Agriculture is responsible for 10 % of UK greenhouse gas (GHG) emissions and 83 % of UK ammonia emissions mainly from livestock rearing and fertiliser use (Defra, 2018b). With proper digestate management practices in place, including storage enclosure, appropriate spreading methods and time of application, and the use of crops derived from sustainable rotational cropping systems (Dale *et al.*, 2010), AD can contribute towards the mitigation of GHG emissions from conventional waste management.

Financial support is available for farmers to implement these mitigating measures. For example, the Farming Ammonia Reduction Grant Scheme helps farmers invest in a coverage (UK Government, 2018). Direct payments to farmers are likely to change in the near future, away from payments based on the amount of agricultural land owned and towards the extent of measures taken by farmers to improve the sustainability of their businesses (ADBA, 2018).

Manure is the most abundant organic material available for AD. Most organic waste in the UK comes from manure and slurry, with an estimated 90 million tons a year, while around 16 million tons comes from food and drink waste (OFT, 2011). Manure has a high nitrogen content, a low C/N ratio, high buffer capacity (or high alkalinity), and relatively low biogas yield. Due to their abundance and properties, manures and slurries are sought after substrates for anaerobic digestion.

Feedstocks used for AD must meet sustainability requirements based on GHG emissions and land use efficiency. Moreover, 50 % of biogas yield has to come from organic materials derived from waste or residues (ADBA, 2018). These constraints are likely to increase the uptake of manures and slurries, and other waste streams, in the feedstock mix in new biogas installations.

There are approximately 218,000 farm holdings in the UK with an average farm size of 80 ha.; half are less than 20 ha (Defra, 2018b). Circa 41,000 farms have more than 100 ha of land, enough to feed an AD system (presentation from Farm Renewables, UK AD Expo 2018, Birmingham). There are approximately 329 operational agricultural biogas plants in the UK, hence there is still considerable room for further deployment of on farm AD systems in the UK to tap into this enormous amount of biomass resource.

The high initial capital cost and low return on investment are the biggest barriers to further deployment of AD. Without improvements in the efficiency of the biochemical processes or technological breakthroughs, reductions in the initial capital expenditure are unlikely to occur. Viability of small-scale systems is going to be even more challenging with the phasing out of the FITs for electricity generation. With the upcoming changes in energy policy, it is time to review the current state of on farm AD of livestock waste and agricultural residues with a focus on the challenges and opportunities.

1.1. Aim

The aim of this research is to explore the geographical locations and the scale of opportunities for deployment of new on-farm anaerobic digestion (AD) systems in the UK, in order to enhance resource recovery and utilise existing biosolids, such as manures and crop residues.

This was done by creation of an integrated biomass resources management tool. The tool combines the capabilities of Geographical Information Systems (GIS) to quantify biomass resources and locate them in space, at various spatial scales, with an Excel-based biogas calculator which designs AD installations and investigates the economic viability of mobilizing these resources for biogas production.

Operators of agricultural biogas plants were surveyed to gain an insight into the operational challenges, costs and benefits of existing on-farm AD plants. The information gathered was then used to corroborate the model underlying the biogas calculator and highlight issues that hinder the utilization of the biomass via AD.

Finally, conclusions were drawn in relation to the amount of un-utilised agricultural bioresource (manures, crop residues etc) which can be economically processed into biogas and fertiliser via on-farm AD processes, in relation to their geographical distribution in the UK.

1.2. Thesis structure

Chapter 2 reviews the literature on various aspects of anaerobic digestion of livestock waste including the description of the biochemistry of AD, modelling approaches, applications, the quantification of the biomass resource potential, fertiliser value of digestate, implications on water quality, barriers and drivers, economics, the efficiency of biogas installations and life cycle assessment. This chapter concludes with a subsection highlighting the gap in the literature and outlining the more detailed aims and objectives of this research.

Chapter 3 describes the methodology used to develop the land use and manure resource management tool in GIS. This section ends with the description of the method applied to evaluate the locations and capacities of new on farm biogas installations to achieve a hypothetical policy target on livestock waste utilization via AD.

Chapter 4 describes the methodology adopted to create the Excel based biogas calculator for economic assessment, including the development of a design calculation framework for AD installations. The tool takes information about feedstock composition and amount, designs a suitable AD installation based on kinetics, stoichiometry and mass balances analysis, and then evaluates the economic outcomes in relation to different biogas valorisation routes and renewable fertiliser generation.

Chapter 5 presents the results of the application of the GIS based biomass resources management tool, at various geographical scales, in order to quantify the untapped biomass potential arising from livestock waste in England and in the area taken as a Case Study. This approach indicates where biosolids resources are located throughout the UK and highlights the “hotspots” where suitable densities of feedstock, or feedstock blends, are available within sensible geographical distances. This chapter ends with the results from the application of the spatial analysis method to evaluate the locations and capacities of new on farm biogas installations.

Chapter 6 describes the results from the evaluation of the Excel based AD biogas calculator compared to the operational and financial data collected via interviews and questionnaires from the eight case studies. This includes observations on the current state of on farm AD in England and an evaluation of the VS degradation efficiency of the biogas installations.

Finally, Chapter 7 presents overall conclusions, some comments on potential limitations of the study, and hence some suggestions for future work.

2. Literature review

. An overview is given of the current state of AD technology and advancements based on a review of the scientific literature. AD technology and its various applications were examined from different angles, including:

- The key parameters used in practice to characterize the organic material, and the techniques to measure them.
- An overview of various modelling approaches developed to describe the biochemical reactions involved during anaerobic digestion.
- Discussion of results from previous studies on the quantification of biomass resource potentials arising from livestock waste from the UK, and other parts of the world.
- Discussion of costs, benefits and implications of using digestate as an organic fertiliser compared to manufactured fertilisers, and the perception of the fertiliser value of digestate.
- The impact of digestate spreading to land on surface water quality.
- Barriers and drivers to the implementation of on-farm AD based on surveys of the willingness of farmers to invest on AD.
- The economics of biogas production via AD processes.
- The efficiency of operational agricultural biogas plants.
- Life cycle assessments of AD.

This chapter concludes with the identification of knowledge gaps and defines the necessary steps to try and address them in this research.

2.1. Waste characterization

Anaerobic digestion is a natural biochemical process occurring in oceans and soils mediated by specific microbial communities under anaerobic conditions. The process converts organic carbon into its most reduced form, i.e. methane, and most oxidized form, i.e. carbon dioxide. The stoichiometry of this biological process is described by the Buswell equation (Symons *et al.*, 1933):

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{7c}{4}\right) H_2O$$
$$= \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} - \frac{5c}{8}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 + c\, NH_4HCO_3$$

Equation 2-1

From Equation 2-1 it follows that the theoretical bio-methane potential of any organic waste can be calculated via Equation 2-2, which is normalised to STP conditions of 0 °C and 1 atm:

$$BMP_{Th} = \frac{\left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) \times 22.4}{12 \times n + a + b \times 16 + c \times 14}$$

Equation 2-2

Measuring volatile solids (VS) in solid waste management is important to determine the biodegradable fraction of waste. COD is the equivalent standard metric used in the wastewater industry that measures the amount of oxygen needed to fully oxydise organics. The measurement of total COD of bio-solids is quite challenging (Buffiere *et al.*, 2008). COD is calculated with the following stoichiometric relationship:

$$C_nH_aO_bN_c + \left(n + \frac{a}{4} - \frac{b}{2} - \frac{3c}{4}\right) O_2 = n\, CO_2 + \left(\frac{a}{2} - \frac{3c}{2}\right) H_2O + c\, NH_3$$

Equation 2-3

The amount of COD needed to oxidise one unit mass of volatile solids is expressed by Equation 2-4 (Raposo *et al.*, 2011):

$$COD_{Th} = \frac{\left(2n + \frac{a}{2} - b - \frac{3c}{2}\right) \times 16}{12 \times n + a + b \times 16 + c \times 14}$$

Equation 2-4

By combining Equation 2-2 and Equation 2-4, the theoretical bio-methane potential can be defined in terms of methane produced per unit mass of COD consumed, hence:

$$BMP_{Th,COD} = \frac{\left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) \times 22.4}{\left(2n + \frac{a}{2} - b - \frac{3c}{2}\right) \times 16}$$

Equation 2-5

Equation 2-5 results in approximately 0.35 L CH_4 g of COD^{-1} consumed under STP conditions (0 °C and 1 atm). The theoretical bio-methane potential is indicative of the maximum methane yield from a substrate. However, several factors mean that the actual bio-methane potential of organic waste isalways lower than the theoretical one (Angelidaki *et al.*, 2004):

- Part of the COD content, which is estimated at between 3 and 15 % by weight of total influent COD (Raposo et al., 2011), is used for microbial growth and maintenance, rather than biogas formation.
- Part of the influent COD short-circuits the reactor due to inefficiencies in the digestion process, and therefore remains undigested.
- Part of COD is recalcitrant to microbial biodegradation, i.e. lignocellulose, and is therefore effectively inert in terms of biogas production.

The Bio-Methane Potential (BMP) test is widely used to measure the amount of methane produced per unit mass of volatile solids in biosolid waste. The sample of organic material is kept under anaerobic conditions for 30 to 60 days at a constant temperature of 35 °C. The volume of methane produced over time is measured to render typical BMP curves. Standard experimental protocols to measure BMP have been developed by Hansen *et al.* (2004) and Angelidaki *et al.* (2009). However, the reproducibility of these experiments is still challenging, as the results are susceptible to the effects of various factors, including the type of inoculum and the inoculum to substrate ratio.

BMP curves show the cumulative methane production over time. The ultimate BMP is the maximum achievable BMP after infinite digestion time, which can be calculated by fitting kinetic models such as first order kinetic, Gompertz, or dual pooled first order kinetic model (Xie *et al.*, 2016) to the BMP curves. BMP tests provide essential information on the kinetics of anaerobic digestion, and biodegradability potential, to assist with AD bioreactor design. Although BMP is indicative of the biogas potential of a feedstock, care must be taken when using typical BMP values reported in the literature.

In fact, BMP can vary remarkably even for the same feedstock (Labatut *et al.*, 2011). For example, the BMP of crop based feedstocks depends on the time of the harvest (Amon *et al.*, 2007) and storage conditions. BMP of manures and slurries depends on animal diet, type of collection system, bedding material and storage time. Nevertheless, typical BMP values are available and suitable for the prediction of biogas yield from a feedstock, or feedstock mix, in feasibility studies.

For design purposes, it is good practice to fully characterize the feedstock. This involves the measurement of BMP (BioMethane Potential), TS (Total Solids) and VS (Volatile Solids), TKN (Total Kjeldahl Nitrogen,) COD_T (Total COD) and COD_S (the Soluble fraction of COD). Arnell *et al.* (2016) propose an affordable and pragmatic approach to determine model inputs to the internationally recognised IWA ADM1 model (Batstone et al., 2002). It should be noted that a comprehensive characterisation of a feedstock is essential for dynamic modelling, but this is not the aim of this project.

Elemental analysis and VS fractionation should be carried out as well. VS fractionation is a method to measure the main components of the VS fraction, including carbohydrates, proteins, lipids, hemicellulose, cellulose, lignin and VFAs (Volatile Fatty Acids). VS fractionation is carried out according to the methodology developed by van Soest (Van Soest, 1963). Assuming a chemical formula for each VS component (Jensen *et al.*, 2013), Table 2-1 shows the corresponding theoretical CODs and BMPs as calculated via Equation 2-4 and Equation 2-5:

Table 2-1: Theoretical BMP and COD calculated, assuming chemical formulae for each VS component.

VS component	Formula	Theoretical BMP ($L\ CH_4\ g\ VS^{-1}$)	COD ($g\ COD\ g\ VS^{-1}$)
Lipids	$C_{57}\ H_{104}\ O_6$	1.012	2.891
Proteins	$C_5\ H_7\ O_2\ N$	0.495	1.414
Carbohydrates	$C_6\ H_{10}\ O_5$	0.414	1.184
Lignin	$C_{10}\ H_{13}\ O_3$	0.726	2.075
VFAs	$C_2\ H_4\ O_2$	0.373	1.066

Lignin is the recalcitrant fraction of VS and is effectively inert in terms of biodegradation. Carbohydrates include sugars, starch, cellulose and hemicellulose, which are all biodegradable substrates. However, cellulose issusceptible to bio-degradation to a certain extent, depending on its accessibility to microorganisms. VS fractionation is rarely carried out in practice for design purposes. However, it is important in research to explore the correlation between each of the main VS components and the resultant BMP, to enhance the predictive capacity of the analysis in relation to biogas production.

This correlation has been investigated via various regression models for a broad range of substrates. Most studies aim to correlate BMPs or BD (BioDegradability) (Dandikas *et al.*, 2015; Herrmann *et al.*, 2016) to the refractory fraction of the organics, namely cellulose and lignin. BMP tests are time consuming hence alternative methods (Lesteur et al., 2010) to measure the biodegradability of the organic matter have been developed, tested and compared with the standard BMP test. Infrared spectroscopy is a promising, cheap and easy-to-use technique to measure the biodegradability and kinetic properties of bio-waste despite the demanding calibration phase (Lesteur *et al.*, 2011).

2.2. Modelling approaches of anaerobic digestion

The IWA ADM1 model (Batstone et al., 2002) is the standard, internationally recognised mathematical model to simulate the biochemical reactions involved in the anaerobic degradation of organic substrates into methane and carbon dioxide. ADM1 describes the anaerobic biological processes of the digestion of organic matter into four steps, including a preliminary extracellular disintegration and hydrolysis stage, and three intracellular steps: acidogenesis, acetogenesis, and methanogenesis, as shown in Figure 2-1.

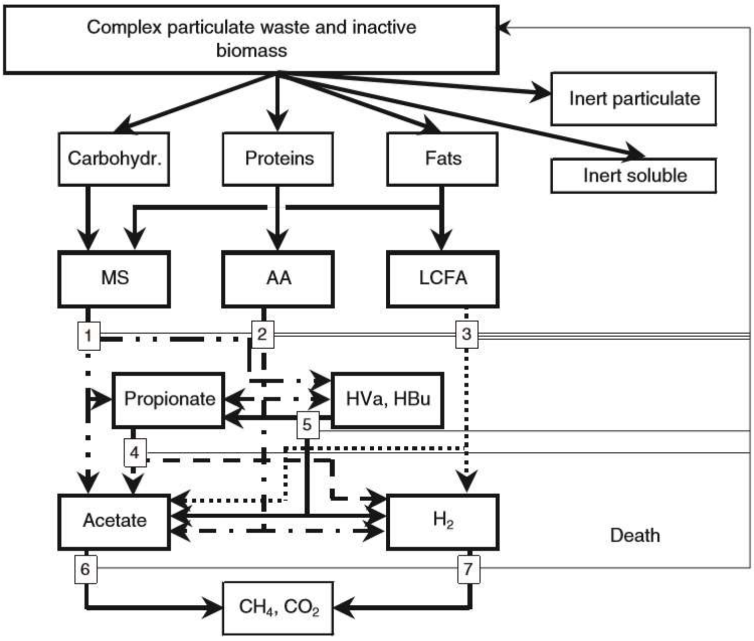


Figure 2-1: The reaction chain of the anaerobic digestion of organic materials. MS, AA and LCFA stands respectively for monosaccharide, ammino acids and long chain fatty acids. HVa and HBu represent respectively valerate and butyrate. This figure has been taken from Batstone *et al.* (2002).

The disintegration step involves the breakdown of particles and composites, including the products of biomass decay, into carbohydrates, proteins, lipids and inerts. The disintegration step is not included in plant-wide modelling of AD sewage bio-solids in waste water treatment works where variables in the IWA Activated Sludge Model (ASM) (Henze, 2002) are mapped directly onto carbohydrates, proteins, lipids and inerts in ADM1 via calculation interfaces (Nopens *et al.*, 2009).

During hydrolysis, carbohydrates, proteins and lipids degrade into their monomer components that are then easily broken down by bacteria. Hydrolysis is the rate-limiting step of the overall biochemical reaction (Vavilin *et al.*, 1996). The disintegration and hydrolysis steps are modelled by first order kinetics whereas the remaining biochemical reactions are well described by Monod kinetics (Giraldo-Gomez, 1991).

In ADM1, hydrolysis is well described by the mechanism illustrated by Vavilin *et al.* (1996), with reactions occurring at particle surfaces colonized by bacteria which produce enzymes to catalyse biodegradation reactions. In their review on hydrolysis Vavilin *et al.* (2008) show that a first order kinetics model is valid for high biomass to substrate ratios, while Contois or two-phase models are more appropriate to describe more complex hydrolytic processes.

Acidogenesis degrades monosaccharides and amino acids into organic acids and hydrogen. Acidogenesis is the fastest step in AD thanks to higher free energy yields. The most important acids produced during acidogenesis from monosaccharides are acetate, propionate and butyrate. Acetogenesis converts organic acids into acetate, hydrogen and carbon dioxide as electron acceptors. Methane and carbon dioxide are produced via two different routes, hydrogenotrophic methanogenesis and acetoclastic methanogenesis.

Two different main types of microbes are involved in anaerobic digestion: bacteria in the hydrolysis, acidogenesis and acetogenesis steps and archaea in the methanogenesis step. Both bacteria and archaea have proven to be sensitive to changes in temperature, feedstock composition and process parameters such as Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT), whereas the methanogens seem to be more sensitive to Volatile Fatty Acids (VFA) and ammonia levels (Weiland, 2010).

A comprehensive mapping of microbial communities involved in anaerobic digestion, and the relationship between microbial community dynamics and environmental parameters, are important to improve the accuracy of current standard AD models, and the understanding of the impact of microbial community structure on digester performance (Mata-Alvarez *et al.*, 2014).

The modelling of physicochemical processes in ADM1 still lacks details needed for a thorough description of acid-base equilibrium, ion speciation and pairing, mineral precipitation, gas-liquid-solid equilibrium, mass transfer and pH modelling. Physical and chemical processes such as ion association and dissociation, pH calculation and gas-liquid exchanges are included in ADM1 as algebraic equations since they are faster processes than the biological reactions described by differential equations. Liquid-solid processes leading to mineral precipitation and solubilization are difficult to model. They are still the focus of research to develop robust and reliable models, hence they are not included in the ADM1 model. Hydrogen, pH and free ammonia inhibitions are part of the standard model (Yenigün *et al.*, 2013).

Various lab experiments and operational biogas plants have demonstrated that stable digestion can occur at high concentrations of ammonia thanks to the ability of microorganisms to acclimatize to this environment (Yenigün *et al.*, 2013). Ammonia inhibition arises along with a building up of VFAs in the digester. Methanogen bacteria are the most sensitive to ammonia inhibition. A wide range of inhibitory ammonia concentrations between 2 and 5 g L^{-1} are found, although these thresholds can be exceeded if microorganisms can acclimatize (Chen, 2008). Various heavy metals, organics and antibiotics can also have inhibitory effects on anaerobic bacteria (Chen, 2008)

During anaerobic digestion sulphur is reduced to sulfide by sulphate reducing bacteria (SRB). These bacteria use a wide range of substrates to grow, hence they compete with most of the anaerobic microorganisms after hydrolysis (Kalyuzhnyi and Fedorovich, 1998). SRB compete with acetogenic and methanogenic bacteria on the same substrates. According to thermodynamics SRB should outcompete acetogens and methanogens microorganisms. Fedorovich *et al.* (2003) model sulphate reduction in anaerobic digestion and incorporate it into the ADM1.

The ADM1 model can incorporate modules to extend its modelling capabilities. For instance, interfaces have been developed to transform practical organic waste characterization into ADM1 model inputs, i.e. carbohydrates, proteins and lipids, based on COD and charge balances (Kleerebezem *et al.*, 2006; Zaher *et al.*, 2006; Arnell *et al.*, 2016), and degradation kinetics (Girault *et al.*, 2012). Other interfaces allow evaluation of the energy balance of the biochemical process (Lübken *et al.*, 2007). ADM1 has been applied to a wide range of AD processes including mono-digestion and co-digestion of agricultural waste (Galí *et al.*, 2009), two-stage digestion (Blumensaat *et al.*, 2005), modelling of the start-up phase (Normak et al., 2015), and an industrial scale biogas plant treating cattle manure and food waste (Biernacki *et al.*, 2013).

The complexity of ADM1 lies in the estimation of the large number of kinetic parameters and in the numerical resolution of the numerous and very non-linear differential algebraic equations. Parameter estimation and identifiability are also major challenges in modelling (Donoso-Bravo *et al.*, 2011). ADM1 should incorporate new metabolic pathways for sulphur reduction, biological phosphorus removal, methane and nitrogen reactions, and hydrogen conversion into methane for renewable energy storage (Batstone et al., 2015). Simpler mathematical models of AD are based on kinetics describing microbial growth and substrate consumption. Table 2-2 summarizes the most common kinetics found in the literature (Xie *et al.*, 2016).

Table 2-2: Description of the main kinetic models to simulate microbial growth and substrate consumption (Xie *et al.*, 2016).

Model	Equation	Legend
First order kinetic	$-r_S = -k \times S$ Equation 2-6	S is substrate concentration (g L^{-1}) k is the first order kinetic constant (d^{-1}) t is time of digestion (d)
Monod	$-r_S = -\frac{\mu_m}{Y} \times \frac{SX}{K_S + S}$ Equation 2-7	X is the microorganism concentration (g L^{-1}) μ_m is maximum specific growth rate (h^{-1}) Y is the growth yield coefficient K_S is the half saturation coefficient (g L^{-1})
Contois	$-r_S = -\frac{\mu_m}{Y} \times \frac{SX}{K_X X + S}$ Equation 2-8	K_X is Contois kinetic constant (g L^{-1})
Haldane	$-r_S = -\frac{\mu_m}{Y} \times \frac{SX}{K_S + S + S \times \left(\frac{S}{K_I}\right)^{n_H}}$ Equation 2-9	K_I is the inhibition constant n_H is the Haldane index (n = 1 or 2)
Chen and Hashimoto	$-r_S = -\frac{\mu_m \times X}{Y} + \frac{(S_0 - S)}{HRT}$ Equation 2-10	S_0 is the initial substrate concentration (g L^{-1}) HRT is hydraulic residence time (d)
Modified Gompertz	$BMP(t) = BMP_o \times exp\left\{-exp\left[\frac{R_{max} \times e}{BMP_o}\right] \times (\lambda - t) + 1\right\}$ Equation 2-11	$B(t)$ is the cumulative methane yield (L CH_4 kg VS^{-1}) B_0 is the ultimate methane yield (L CH_4 kg VS^{-1}) R_{max} is the maximum methane production rate (L CH_4 kg VS^{-1} d^{-1}) e is Euler's number equal to 2.718 λ is the lag phase (d)
Dual pooled first order	$BMP = BMP_o \times \left[1 - \alpha \times exp(-K_f t) - (1 - \alpha) \times exp(-K_L t)\right]$ Equation 2-12	α is the ratio of rapidly degradable substrate to total biodegradable substrate K_f is the rate constant for rapidly degradable substrate (d^{-1}) K_L is the rate constant for for slowly degradable substrate (d^{-1})

By applying a mass balance to a CSTR AD reactor and assuming a first order kinetic model to determine substrate removal, Linke (2006) and Mähnert *et al.* (2009) show the relationship between biogas yield and HRT represented by Equation 2-13:

$$BMP = \frac{HRT \times k \times BMP_o}{HRT \times k + 1}$$

Equation 2-13

Here, BMP_o is the bio-methane potential of the substrate at infinite HRT (L of CH_4 kg of VS^{-1}), k is the first order kinetic coefficient (d^{-1}) and *HRT* is the Hydraulic Residence Time (d). This equation shows how at infinite HRT, BMP equals the maximum BMP achievable for the specific substrate. In the case of co-digestion Equation 2-13 can be rearranged as follows (Linke *et al.*, 2013):

$$BMP = \frac{HRT \times k_{Mix} \times BMP_o^{Mix}}{HRT \times k_{Mix} + 1}$$

Equation 2-14

Where BMP_o^{Mix} and k_{Mix} in Equation 2-14 are respectively the ultimate BMP and the overall first order kinetic degradation constant of the feedstock mix. The BMP of the feedstock mix is calculated as a weighted average, where the weight is the share of each component in the total volatile solids content. This approach predicts the resulting BMP of the feedstock mix accurately (Hashimoto, 1983; Linke *et al.*, 2013):

$$BMP_o^{Mix} = BMP_o^{manure} \times \%VS_{manure} + BMP_o^{crops} \times (1 - \%VS_{manure})$$

Equation 2-15

Where $\%VS_{manure}$ is the proportion of volatile solids associated with manure, BMP_o^{manure} (m^3 CH_4 kg VS^{-1}) and BMP_o^{crops} (m^3 CH_4 kg VS^{-1}) are respectively the bio-methane potentials at infinite HRT of manure and crops. Similarly, Equation 2-16 calculates the overall kinetic constant for the mixture (Linke *et al.*, 2013):

$$k_{Mix} = k_{manure} \times \%VS_{manure} + k_{crops} \times (1 - \%VS_{manure})$$

Equation 2-16

Where k_{manure} and k_{crops} [d^{-1}] are respectively the hydrolysis rate for manure and for crops. Therefore, Equation 2-14 can be rearranged as follows:

$$BMP = \frac{\begin{array}{c} HRT \times \left[k_{manure} \times \%VS_{manure} + k_{crops} \times (1 - \%VS_{manure})\right] \times \\ \left[BMP_o^{manure} \times \%VS_{manure} + BMP_o^{crops} \times (1 - \%VS_{manur}\ )\right] \end{array}}{HRT \times \left[k_{manure} \times \%VS_{manure} + k_{crops} \times (1 - \%VS_{manure})\right] + 1}$$

Equation 2-17

Linke *et al.* (2013) fitted Equation 2-17 to data from German biogas plants fed with cattle manure and crops to model biogas production in the main digester and storage tank. They estimated the four parameters in Equation 2-17 via a non-linear least square method and found the following values:

- BMP_o^{crops} = 420 L CH_4 kg VS^{-1}
- BMP_o^{manure} = 270 L CH_4 kg VS^{-1}
- k_{crops} = 0.2 d^{-1}
- k_{manure} = 0.2 d^{-1}

2.3. An overview of AD and its applications

Optimal C/N ratios for methanogenesis bacteria lie between 20 and 30, even though higher and lower ratios can still ensure stable digestion. The C/N ratio is important to ensure a good nutrient balance (Romero-Güiza *et al.*, 2016). Co-digestion is common practice at biogas installations to achieve higher biogas yields and improved nutrient balance. Nonetheless, in practice it is the operational contingencies associated with feedstock availability that determine feedstock composition.

Anaerobic digestion can occur at different optimal temperature ranges: psychrophilic at temperatures lower than 20 °C, mesophilic between 35 and 40 °C and thermophilic between 55 and 60 °C. The degradation rate increases with temperature and so does digester instability due to ammonia inhibition (Yenigün *et al.*, 2013). Hydrolysis occurs at pH between 5 and 6, whereas methanogenesis occurs at higher pH between 7 and 8, hence controlling the reactor pH is key for stable digestion. Buffer systems based on carbonate equilibrium prevent pH fluctuations in single digester plants. Two-stage AD can be used to partition hydrolysis and methanogenesis into separate tanks to optimize each independently, and hence biogas production overall.

Various reactor configurations are used in AD such as batch, plug flow and CSTR. The latter is the most common type in practice. Recent research advancements have led to the development of other configurations, such as upflow anaerobic sludge blanket (UASB), anaerobic membrane bioreactor (AnMBR) and fluidized bed, to improve design and reactor efficiency (Batstone and Virdis, 2014).

Legislation in Germany requires that sludge treated via anaerobic digestion must reach full degasification after storage to prevent any unwanted residual methane emissions. This entails that most agricultural biogas plants have two main digesters working in series followed by a storage tank, with inherent redundancy built in the system, leading to long residence times of over 100 days (Ruile *et al.*, 2015). In the UK there is no such legislation that requires the complete degasification of the feedstock, and hence single stage digesters are common.

Feedstock pre-treatment changes the physical and chemical characteristics of the organic material, primarily aiming to make the slowly biodegradable organic fraction and lignin more available to microbial degradation. Conventional physical and chemical treatments such as milling, ultrasonics, and steam explosion can give up to a 30 % increase in biogas production, despite the higher energy requirements and potential side effects on microbiology (Carlsson, 2012).

Alternative strategies that do not involve any pre-treatment have emerged such as integrated biogas production, digester design, co-digestion, and bio-augmentation (Patinvoh et al., 2017). The application at full scale plants of new approaches such as biomass immobilization, nanoparticle addition, bio-augmentation and enzyme addition are still rare due to costs, uncertainty in the efficacy of these treatments, and associated risks (Romero-Güiza *et al.*, 2016).

Energy losses during biogas production are associated with methane leakages and ensiling (biomass storage). The latter can cause energy losses ranging between 8 and 20 % via aerobic decomposition of silages during storage (Köttner *et al.*, 2008). Therefore proper management of the silage clamp via compaction and coverage is of paramount importance (Holm-Nielsen *et al.*, 2009). Post-treatments of digestate are needed if there is not enough land available for spreading, and strict limits to nutrient loads to land are enforced (De Vries *et al.*, 2012a).

Macro (P, N, S) and micro nutrient (Fe, Ni, Co, Se) supplements benefit methane production and process stability. Micronutrients play a key role in enzymatic activity. Fe addition has shown promising results in the enhancement of biogas production. Addition of magnesium to anaerobic digestion for struvite precipitation, and hence valuable phosphorus recovery, involves high costs and risk of pipework clogging, such that redesign of the process is needed.

In-line monitoring systems are pivotal to implement effective AD optimization strategies. At biogas installations in-line systems monitor just a few variables such as pH, temperature, redox potential and gas flow. Titration is the common measurement technique for VFAs. Chromatographic methods are more complex and expensive, but they enable more thorough characterization of VFAs.

New technologies are being tested in laboratory and full scale plants including fluorescence spectroscopy, infrared spectroscopy combined with fibre optics, near infrared spectroscopy (Holm-Nielsen *et al.*, 2009), chemical sensors via electronic “tongues and noses”, chromatography, microwaves, and acoustic chemometrics (Madsen *et al.*, 2011). Some of these techniques are subject to fouling, abrasion of the sensors, and clogging, and most of them need pre-treatment such as solids removal via filtration (Madsen *et al.*, 2011). Analysers for monitoring and control must be robust and simple to use especially for agricultural biogas plants, so these more advanced techniques have limited update in practice.

There is still potential to improve the efficiency of the anaerobic digestion. Normally anaerobic bioreactors operate at OLR values ranging between 4 and 10 kg of VS m^{-3} d^{-1} (Xie *et al.*, 2016). The animal digestive tract is capable of processing up to 400 kg of VS m^{-3} d^{-1} for some insects (Godon *et al.*, 2013), so inspiration may be taken from nature to improve the efficiency of engineered AD reactors.

Anaerobic digestion has evolved into a waste valorization process, leading to the production of value-added chemicals (bioplastics), organics, nutrient recovery (N and P), and energy recovery. Low energy mainline and partition release recovery have emerged as process platforms for nutrient and energy recovery that are ready to implementation at full scale plants. Mixed culture biotechnology, and electron transfer control to produce alternative products, are promising techniques to achieve the bio-refinery concept (Batstone et al., 2014).

2.4. Evaluation of the biomass potential arising from livestock waste

Geographical Information Systems (GIS) are popular software tools used by academia and businesses to enable the integration of digital mapping with databases. GIS has been extensively applied to quantify biomass resource potentials stemming from forestry, agricultural residues, land management, grassland and various other types of biomasses and waste (Lovett *et al.*, 2009; Scarlat *et al.*, 2010; Van Meerbeek *et al.*, 2015; Haase *et al.*, 2016). These quantitative assessments of biomass resource potentials are instrumental to highlight spatial patterns, the scale of opportunities, and to identify strategic locations for the deployment of renewable energy production systems.

The creation of GIS-based tools for resource mapping helps to answer research questions in biogas research and potential applications. Waste arising from animal husbandry is the most abundant and versatile substrate for AD. Estimates of manure and slurry production mostly rely on agricultural censuses, conducted by national Ministries of Agriculture across Europe, at various spatial scales. In the UK, Defra is responsible for undertaking the full agricultural census every 10 years and regular surveys in between (DEFRA, 2017).

There are two main challenges associated with the quantitative spatial estimation of manures and slurries: (i) it is difficult to pinpoint the exact location of farms due to data protection for single farms, and (ii) only resources that are collectable and stored effectively can be used for AD. As a result, the spatial resolution of livestock waste mapping is often quite coarse. This limitation can be overcome by spatial analysis techniques that can infer the value of a variable at finer spatial length scales.

For instance, if variable z is the total number of cattle in a Local Authority (LA) then it is possible to infer the spatial pattern of the cattle variable within the overall LA, if auxiliary information is available on different land use within the LA. In mathematical terms this translates into a function $z = f(x,y)$, where z is the value of the variable and x and y are the geographical coordinates within the LA. In the scientific literature this is regarded as the areal interpolation problem (Goodchild *et al.*, 1993), aiming at transferring variable z from source zones, i.e. the overall LA area, to target zones, i.e. smaller areas.

Comber *et al.* (2008) created the national agricultural land use dataset for England and Wales showing the theoretical biomass resources from manures, slurries, energy crops, and crop residues at a 1 km^2 resolution. They used a dasymetric mapping technique combined with a pycnophylactic interpolation method to obtain a land use database starting from agricultural census data at the parish level (parishes being smaller, and hence a subset of the LA).

ADAS Ltd. refined this model to create the MANURE-GIS national inventory of livestock manure for Defra (ADAS, 2008). Based on information gathered from national surveys of organic fertiliser usage, they were able to assemble an inventory with assumptions on annual excreta production by livestock group, category and age, excreta apportionment by time of year, and type of manure (i.e. either slurry or farmyard manure). In addition, manure is further divided into a fraction that is immediately spread to land and a fraction that is stored. National inventories of livestock waste and other waste streams suitable for AD have been created with similar approaches in other regions of the world (Dionisi *et al.*, 2018), including future projections of biomass resource availability (Batzias *et al.*, 2005).

The scale of the geographical focus of the biomass resource mapping analysis can be local, regional, national, or transnational. For example, Haase *et al.* (2016) focussed their investigation on five regions within Europe, namely England, France, Germany, Belgium and the Netherlands, to examine the biomass potential arising from crop residues. Meyer *et al.* (2018) upscaled the study to the whole of Europe to estimate the biomass and energy potentials from agricultural residues including manures.

Meyer *et al.* (2018) projected these potentials to 2030 to show that the available biomass and energy from cow, pig and poultry manures amount collectively to between 83 and 122 M tonne per annum of dry solids and between 670 PJ and 890 PJ of energy per annum. Despite the current negligible contribution (2-3 %) of biogas production from such residues to the average gross energy consumption in Europe, the use of these resources is crucial to achieve the sustainability requirements set by regulations on feedstocks and to ensure further growth of biogas deployment in Europe.

Scarlat *et al.* (2018) looked at the European wide biomass and energy potential from manures, by creating density maps at 1 km^2 spatial resolution, to highlight local hotspots that can ensure financially viable conditions to build an AD plant. They showed that about 861 M tonnes of fresh manures can be collected for biogas production, which is equivalent to 577.3 PJ of energy potential or the entire yearly natural gas consumption of Belgium. These estimates are more conservative than those of Meyer *et al.* (2018), since they just take into account the fraction of manure that is collectable. Scarlat *et al.* (2018) also identified the best locations to install biogas plants without taking into account current competition for feedstocks from existing operational sites.

Studies of biomass resource mapping are a prerequisite to the identification of strategic AD biogas facility locations. An initial suitability analysis is usually performed to identify areas that are suitable for the development of biogas installations, followed by optimal facility siting analysis (Sliz-Szkliniarz *et al.*, 2012; Zubaryeva *et al.*, 2012). For instance, Dagnall *et al.* (2000) looked at the optimal sites to locate centralised AD plants in East Anglia for treating pig and fowl manures, in proximity of major roads and grid substations, with a limitation on manure collection areas with a maximum radius of 10 km.

Location is a key factor to ensure low operational costs and easy access to the facility, via minimisation of transport requirements. This has become a whole new area of research, called location science (Farahani *et al.*, 2010), which borrows mathematical methods from operations research. These methods define an objective function subject to a set of constraints that can take various forms depending on the objective (Owen *et al.*, 1998).

For instance, the objective could be to find a set of locations that maximize the number of farms served by an AD plant within a cut-off distance (Thompson *et al.*, 2013) or that minimize the demand-weighted travel distance between demand and facilities (*p*-median problem) (Höhn *et al.*, 2014). Supply and demand are rather vague concepts in bioenergy systems. In the context of biogas production from livestock waste, supply is defined as the spatially distributed biomass potential available for use in AD, whereas the potential locations of AD biogas installations represent the demand for feedstock (Bojesen *et al.*, 2014).

Strategic planning helps minimize costs of biogas production at a regional and national level by identifying optimal locations and plant capacities. Bojesen *et al.* (2015) showed how planning can contribute to achieve renewable energy policy targets in a cost-effective way. They created a GIS-based tool to map the spatial distribution of biomass resources from animal waste in Denmark, projected to 2020 via Markov chains. Then they applied the *p*-median problem combined with a spatial interaction model to optimally locate new biogas facilities. Spatial interaction models also aim to account for resource competition due to existing or other planned biogas installations.

Comber *et al.* (2015) modified the standard algorithm of the *p*-median problem to include competition for biomass resources in a region of East Anglia in England. O'Shea *et al.* (2016) explored the optimal utilization of cattle manure and grass silage in Ireland to produce bio-methane to inject to the gas grid at the least possible cost. They formulated an optimization problem to maximize the NPV (Net Present Value) and minimize the LCOE (Least Cost of Energy) with the aim of finding the best locations for the installation of a subset of new bio-methane plants at predetermined gas grid injection points.

2.5. The fertiliser value of digestate – benefits and challenges

There is substantial evidence to support the enhanced fertiliser value of digestate compared to untreated manures. Anaerobic digestion does not change the nutrient pool in the feedstock mix, but it changes the proportions of various organic and inorganic compounds. It makes macronutrients (N, P and K) more available for plant uptake compared to raw manure. During digestion, organic nitrogen is mineralised into inorganic forms of nitrogen. The C/N ratio and particularly the C_{org}/N_{org} ratio is a key factor determining the N-mineralisation potential during AD (Jensen *et al.*, 2013).

Eich-Greatorex *et al.* (2018) showed that digestate has the same effect on crop yields as mineral fertilisers, providing an opportunity for sustainable fertiliser replacement, and it is also a good soil conditioner as it improves soil porosity and water retention. Abubaker *et al.* (2012) found that pig slurry shows the highest biomass yield and nitrogen mineralisation capacity (NMC), while AD residues have similar biomass yields but higher NMC and ammonium oxidation rates than mineral fertilisers. Pot experiments (Sogn *et al.*, 2018) showed that digestate application to different soils had the same or enhanced effects on crop yields compared to mineral fertilisers and manures, with the potential to reduce nitrates leaching from fields. This in turn could lead to surface water protection.

Studies based on short and long term field experiments also support the significant fertiliser value of AD residues. Walsh *et al.* (2018) found that during a

3-year field trial, digestate could successfully replace mineral fertilisers without compromising pasture yields. In addition, their findings indicated that digestate increases soil organic matter content without any significant difference in protein content and digestibility of grass produced.

WRAP conducted a 5-year field experiment in the UK to compare the fertiliser value of digestate with manures, food waste digestate, manure-based digestate, compost, and manufacture fertilisers (WRAP, 2016). They focussed on the impact of fertiliser on nitrogen use efficiency, soil structure and biology. Their findings highlighted the following key points:

- The quality of crops was no different with the use of digestates or mineral fertilisers.
- Compost or digestate application provided soil with a boost of nutrients (P, K and S), leading to higher crop yields than bagged fertilisers.
- Nutrient use efficiency of crops, which represents the amount of nitrogen applied to land which is taken up by the crops, was heavily dependent on the time of the year when organic fertilisers are applied to land. Circa 50 % of nitrogen applied in Spring was used by crops in the case of manure-based digestate, dropping to 15 % for Autumn application.
- The application of compost or digestate improved soil quality, especially in the case of lignin rich organic fertilisers such as green compost. For instance, the results showed that the soil organic matter content increased just over 20 % against the benchmark, over 20 years of green compost and farmyard manure application.
- Improvement in soil microbial activity as measured by microbial biomass, and earthworm populations. Another study confirmed these findings and also identified an increase in microbial diversity that could have a positive effect on the ability of the crop plants to suppress pathogens (Sapp *et al.*, 2015).
- Compost and farmyard manure applications decreased soil bulk density, leading to improved physical properties of the soil.
- No changes in top soil metal content were observed in any of these trials.

- Digestate should be spread to land when crops require nutrients, and via appropriate methods that minimize ammonia emissions and nutrient losses, such as via shallow injection.
- Lower N_2O emissions and methane emissions were observed from digestate compared to the application of untreated slurry.

Heslop *et al.* (2012) conducted a similar study in Ireland with a two-year crop demonstration trial of compost, slurry, artificial fertiliser and digestate to arable and grassland on working farms. They observed that compost and digestate applied to arable land are suitable alternative nutrient sources to manufactured fertilisers, that are capable of meeting nitrogen crop requirements, and help increase soil organic matter content.

Further research is needed on long-term field experiments to provide further evidence that digestate application to arable and grassland reduces nutrient losses via run-off and infiltration, under diverse climatic and soil conditions. It is expected that in the long term, nitrate leaching is reduced with digestate application when compared to manures, due to the lower organic nitrogen content in digestate that is susceptible to N mineralisation (UNITO, 2014).

There are some environmental risks associated with the spreading of digestate to land. These include the enhanced emissions of ammonia, the accumulation of metals in soil such as Cu, Zn and Mn, phyto-toxicity, public health concerns, and the degree of product stabilisation (Nkoa, 2014). The spreading method affects ammonia emissions and the N uptake by plants in the fields. If not immediately incorporated into soil, ammonia nitrogen is susceptible to quick volatilization, leading to nitrogen losses to atmosphere, and cancelling the enhanced fertiliser value of digestate (Shi *et al.*, 2018).

Despite the wide range of information in the scientific literature that evidences the enhanced fertiliser value of digestate, and potential savings by replacing manufactured fertilisers, a strong market for digestate has not yet developed. There is a failure in the market of agricultural fertilisers that prevents potential customers from recognising the intrinsic nutrient value of digestate, for various reasons:

- The product is not standardised, mainly due to digestate quality issues related to variability in nutrient contents, the potential presence of pathogens, potential impurities such as plastics, metals and other inert materials, and odour control.
- In regions with intensive livestock farming and high biogas plant density, that are subject to strict regulations on nutrient loads to land via the EU Nitrates Directive (European Commission, 1991), competition to find land available for digestate distribution is strong, leading to higher disposal costs. Hence, digestate can turn from a resource into a burden. Farmers can either treat digestate to produce a fertiliser that is easier to handle and market, or transport digestate over long distances to redistribute nutrients across regions. This is a topical issue in Northern Germany, the Netherlands and Denmark.
- Building the trust of farmers in relation to bio-fertiliser products takes time, and their perceptions are often initially negative.

Tur-Cardona *et al.* (2018) reported that the attitude of farmers towards digestate were mostly affected by the following fertiliser attributes:

- Cost.
- Form of fertiliser (liquid, solid, granular).
- Volume.
- Nitrogen content.
- Organic content.
- Public health.
- Rate of nutrient release.

Nutrient content variability and potentially large volumes mostly influenced the willingness of farmers to pay for bio-fertilisers, even though it was estimated to cost about 76 % of the price of chemical fertilisers (Tur-Cardona *et al.*, 2018). Farmers were inclined to pay more for bio-fertilisers that ensure hygienic conditions, which contain organic carbon, and which comes in solid or semi-solid form. Farmer age and farm size also influence attitude towards the acceptance of organic fertilisers (Case *et al.*, 2017). These studies of the perceptions of farmers indicate key issues to address to develop a market for digestate:

- Develop cost-effective digestate post-treatments to create marketable products.
- Building trust among farmers and other potential customers in other markets and niche outlets for digestate.
- Developing uniformity and standardisation of the product.
- Improving communication and outreaching activities to educate consumers.
- Developing certification of digestate quality by third party agencies.
- Large producers of mineral fertilisers have more bargaining power over small producers of organic fertilisers. Therefore, co-operative approaches between smaller producers, and the creation of brand names can help to build negotiating power.
- Manufactured fertiliser prices are likely to increase in the future due to the expected depletion of phosphorus reserves. Morocco has around 77 % of global phosphorus reserves. This raises concerns over price fluctuations in the future due to political and social instabilities of the country (Cooper *et al.*, 2011), and may result in increased interest in bio-fertilisers.

Digestate dewatering generates a liquid fraction with low dry matter content, typically 3 % by mass, and a solid fraction with a higher dry matter content, typically 25 % by mass. Most of the P ends up in the solid fraction, which is a good soil supplement, whilst N and K is mainly in the liquid fraction, making a good bio-fertiliser. Whilst the liquid fraction of digestate is almost entirely used in agriculture, the solid fraction can service alternative markets such as animal bedding, horticulture, gardening, pelleting for energy production, soil manufacturing, and landscaping or land reclamation (Dahlin *et al.*, 2015).

The liquid fraction of digestate can undergo further physical and chemical treatments to produce a more valuable bio-fertiliser (Monfet *et al.*, 2018). This can ease the handling of this material, making it an attractive fertiliser product. Drying, ammonia stripping and struvite formation, evaporation, and membrane technology are common techniques that have been applied to full scale plants (Shi *et al.*, 2018) with treatment costs range between £4.75 and £6.13 € m^{-3} (Bolzonella *et al.*, 2018). Styles *et al.* (2018) showed that the recovery of nitrogen and phosphorus in the form of ammonium sulphate, after ammonia stripping and struvite precipition, could be more environmentally beneficial than just applying the liquid digestate directly to land.

Digestate is often regarded as a burden. Despite its intrinsic fertiliser value, estimated between £3 and £5 per wet tonne, digestate is often given away or determines a disposal cost (NNFCC, 2016). In Germany, whole digestate prices range between £5 and -£18 per tonne (Dahlin *et al.*, 2015). Negative values mean that digestate producers pay farmers for haulage and spreading on their land. This is the case especially during winter when spreading is not allowed and storage is needed. In the Netherlands, manure disposal costs (the other side of the transaction) for farmers are estimated to range between -£2.93 and £6.19 per wet $tonne^{-1}$. Negative values means that farmers pay the biogas plant to accept manure in regions which experience manure surpluses (Yazan *et al.*, 2018).

2.6. The role of AD to improve water quality in catchments

The EU Nitrates Directive (European Commission, 1991) regulates the amount of nitrogen that can be applied to land, the minimum storage time for slurries and manures, and dictates fixed time windows when organic fertilisers cannot be spread to land. This Directive aims to mitigate nutrient leaching to surface waters from agriculture. In some European countries, such as the Netherlands and Denmark, they see the benefits of these mitigation measures through a decrease in the gross N load to catchment water, detected via nitrate concentration measurements in groundwater and surface waters (Van Grinsven *et al.*, 2012).

Models based on mass balances of nitrogen and phosphorus have been developed to predict the nutrient loads to surface water bodies and groundwater, subject to various environmental and agricultural policies. These models can assist in evaluating the impact of policy scenarios on water quality at various geographical scales. For instance, Velthof *et al.* (2014) found that a reduction of 16 % in N losses to surface water (36 % in the UK), and 3 % of ammonia and 6 % of N_2O to atmosphere (12 % in the UK), can be achieved if policies on water quality from the EU Nitrates Directive were implemented in all 27 member states between 2000 and 2008. These reductions are even more accentuated in countries with intensive livestock systems such as the UK.

The importance of carrying out a quantitative assessment of nutrient losses to water bodies is driven by the detrimental impact that excessive nutrient loads have on the aquatic environment, resulting in eutrophication that depletes oxygen for fish and other aquatic organisms. Phosphorus has been the main focus since it is responsible of the majority of the eutrophication occurrences in Europe (Withers *et al.*, 2007). Whilst enforcing statutory N and P discharge consents to surface water is quite straight-forward for point sources, the prevention and control of diffuse pollution is much more challenging, and often referred to as the "wicked" problem (Patterson et al., 2013).

In the UK a wide range of modelling tools (Silgram *et al.*, 2001; Webb *et al.*, 2006; Strömqvist *et al.*, 2008; Nicholson *et al.*, 2013) are available to simulate the fate of nutrients in soil, groundwater and surface water. The Farmscoper software tool (Gooday *et al.*, 2010) integrates these models to create a comprehensive tool to assess the impact of different environmental policies on emissions to air and water from agriculture. Greene *et al.* (2015) showed that the implementation of on farm mitigation measures could reduce N and P losses by almost 30 % and 15 % compared to the current state. On the other hand, full compliance of all sewage discharges with the European Urban Wastewater Treatment Directive could deliver considerable reductions in P discharges, by 58 % in the UK, but at huge expense for water companies.

DEFRA (2011) set a list of 86 measures to mitigate diffuse pollution from agriculture, including anaerobic digestion of animal manures and slurries. Farmers can maximize the benefits derived from AD if they apply this technology in combination with utilising covered slurry storage, and proper application methods, such as soil injection (Möller *et al.*, 2008), to increase nitrogen use efficiency, reduce ammonia emissions, and reduce mineral fertiliser usage.

The involvement of farmers in the development of environmental policy should be encouraged. Their knowledge is important for scientists to define the most effective strategies leading to the mitigation of diffuse pollution from agriculture (Oliver *et al.*, 2012); Collins *et al.* (2016) surveyed the preferences of farmers towards the 86 measures listed by DEFRA (2011). They demonstrated that the implementation of the 29 mitigation measures that were most attractive to farmers on 95 % of the farms could lead to emission reductions to water and air of approximately 20 % for sediment, 16 % for ammonia, 15 % for total phosphorus, 11 % for nitrate and methane, and 7 % for nitrous oxide, compared to the business as usual scenario, with average additional costs of only £ 3 per ha per year.

Anaerobic digestion of animal waste, i.e. manures and slurries, coupled with proper digestate management in covered storage, and with appropriate timing and methods of spreading, can achieve a reduction in N and P loads to groundwater and surface water. At the same time, AD is consistent with the principles of the circular economy, by closing the nutrients loop, and by reducing the input of mineral fertilisers (Skenhall *et al.*, 2013).

2.7. Barriers and drivers to AD uptake

A survey conducted in the UK (Tranter *et al.*, 2011) asked farmers about their willingness to install AD systems on farms and about their perception of barriers to this kind of initiative. Circa 40 % of respondents considered exploring the AD opportunity. Farmers who were more inclined to invest in AD technologies tended to be younger, more educated, owner-occupiers (rather than tenants), and had bigger farm business sizes, than farmers who were not likely to adopt it.

The likely non-adopters perceived the importance of barriers to AD deployment differently from likely adopters: for example, costs and compliance with tenancy agreements were more important factors for likely adopters than non-adopters, whereas lack of spare labour to run the digester was felt as a barrier more by non-adopters than likely adopters (Tranter *et al.*, 2011). The likely adopters would allocate roughly 21 % of the total farmed land to grow crops for AD, half of it on cereal land. Tate *et al.* (2012) confirmed that the findings of Tranter *et al.* (2011) can be applicable to other renewable technologies. Interestingly anaerobic digestion was found to be the least popular technology among the renewable energies before the introduction of Renewable Heat Incentive (RHI) (DECC, 2011). Table 2-3 summarizes the benefits and barriers perceived by farmers in the UK who have already installed an AD plant on farm.

Table 2-3: Summary of barriers to and benefits of AD for farmers, according to (Bywater, 2011; Tranter *et al.*, 2011).

Barriers	Benefits
• economies of scale, which means that establishment costs are high and return on investment low for on farm AD • planning permission • lack of information available on the technology • high investment in CHP technology and connection to the grid • seasonality of feedstock supply especially slurry • strict regulations on import of off-farm feedstocks • the need of cost-effective and modular small-scale AD plants easy to install and operate • compliance with tenancy agreement • lack of spare labour	• improvement of farm profit • reduction of pollution and contamination risk • reduction of farm's carbon footprint • improvement of manure management • practices and ease of compliance with strict regulations on manures • increase of nitrogen use efficiency • odour abatement • reduction of reliance on mineral fertilisers and fossil fuels • farm diversification • diversion of wastes from landfill • energy efficiency and self-sufficiency

Ge *et al.* (2017) found that farmers in Scotland who diversified their businesses or provided tourism, accommodation and leisure activities were more inclined to adopt renewable energy technologies, such as solar and bioenergy. The age of the owner had a huge impact on the attitude towards AD, with younger farmers being more open to embrace new technologies. Finally, farms with high energy demand, or with mostly rough grazing land, or land with low agricultural potential, were also more likely to show a positive attitude towards renewables.

The extent of proliferation of AD plants is mainly dependent on the implementation of waste and energy policies and government subsidies on electricity and heat production. For instance, the introduction of binding targets on the production of renewable energy with the Renewable Energy Directive (RED) (European Parliament, 2009) and government subsidies have boosted the uptake of AD across Europe, although they might not be adequate to meet the targets set by EU legislation on bio-energy production (Bartolini *et al.*, 2017). The landfill levies and incentives to reduce waste have contributed to make AD a more competitive waste management option (Edwards *et al.*, 2015). In addition, energy security and strict regulations on manure management are relevant factors affecting the degree of AD deployment in Germany and Australia (Wilkinson, 2011).

AD biogas plant design needs to be tailored to the farm needs. Carrosio (2013) highlighted the risk of institutional standardisation in the Italian AD industry that occurred in the early stages of dissemination and deployment of the technology after the introduction of government subsidies. He identified three mechanisms leading to institutional isomorphism:

- Normative: most farmers rely on professional advice for the choice of the technology, and this tends to converge towards standardised technology packages.
- Coercive: farmers operate within a common legal framework.
- Mimic: farmers are more willing to adopt technological solutions that have already proven to work well on other farms.

A top-down approach has driven the deployment of AD systems in the Italian biogas sector. As a result, on farm AD systems feature standardisation with homogeneous characteristics that do not fit farm-specific needs, and do not allow local communities to benefit from it. Conversely, in the northern region of South Tirol, biogas cooperatives with a bottom-up approach, supported by community-based energy initiatives (Carrosio, 2013), have dominated, suggesting that socio-economic factors determine the way AD is implemented (Hoffman *et al.*, 2010).

Community digesters are an option to overcome limitations related to the economies of scale and risk adverse attitudes of farmers (Panoutsou, 2008). Despite the fact that the economy of scale determines the attractiveness of AD amongst farmers, biogas cooperative approaches can persuade small farms with more than 50 dairy cows to show positive attitudes towards AD (Swindal *et al.*, 2010). The level of education of a farmer, concern over water pollution caused by farming, and scepticism towards organic farming, seem to be predictors of interest towards community digesters (Swindal et al., 2010).

2.8. The economics of biogas production

Decision support tools help to investigate costs, benefits and the sustainability of anaerobic digestion. The main limitation of these evaluation tools is that they are generic. This entails that evaluation tools cannot capture the inherent case-specific nature of AD biogas installations, that vary according to the type of feedstock mix, plant design, pre-treatment methods, biogas end use, transportation, and digestate management. Nonetheless, they still provide useful guidance for scenario evaluation and decision making.

The Andersons Centre developed an Excel based calculator (Redman, 2008) to enable viability assessment of AD projects based on average default values for biogas yields and costs, with the option for the user to input their own data. Anderson *et al. (*2013*)* developed an Excel based evaluation tool available on line, allowing a certain degree of flexibility to adapt the assessment to the specific farm and biogas end uses. Wu *et al.(*2016*)* built on previous work to develop an Excel-based calculator that allows adjustments of biogas yield with temperature, dead time, and imperfect mixing. Another category of evaluation tools evaluates the energy and GHG balances across the whole farm (Styles et al., 2016), or at the AD biogas plant, to comply with sustainability requirements on feedstocks (NNFCC, 2015).

Research is moving towards the integration of economics and sustainability of anaerobic digestion into a single tool. For instance, Usack *et al.* (2018) created a comprehensive tool to examine the feasibility of AD projects, that combines techno-economic assessment based on the ADM1 modelling framework with environmental impact assessment according to LCA principles.

Köttner *et al.* (2008) applied an economic calculator to eight biogas case studies of various farm types across Cornwall, to investigate the viability of on farm AD plants. They concluded that the investment in AD was viable only for installed capacities higher than 250 kW_{el} which were mostly fed with slurries, highlighting the challenges of seasonal fluctuations in cattle slurry supply through the year.

The implementation of AD in farming systems inevitably brings about changes in manure management practices, and in the farm business as a whole. Jones *et al.* (2013) developed a model based on linear programming, to understand the impact of AD projects on net profit margin of farm businesses, and on the decision making of farmers on crop selection and land use allocation. They found that, in England, AD was economically viable for medium to large systems up to 500 kW nominal capacity for arable farms, whereas for large dairy farms with 610 ha and 550 head dairy herd, an AD plant with a capacity of 195 kW and fed almost entirely by manure would add a marginal 6 % to the farm net profit.

It is important for farmers that on farm AD systems fed predominantly with manures are more cost effective over their lifetime than fertiliser systems based on conventional manure management. Lukehurst *et al.* (2015) showed that AD was still advantageous compared to conventional manure management practices for investment costs up to approximately £150,000, even if energy prices doubled and RHI decreased by 20 % across all scenarios. So a shift of policy focus is needed away from financial incentives to energy production and towards potential reductions in greenhouse gas emissions (Jones *et al.*, 2013; Lukehurst *et al.*, 2015).

On-farm co-digestion of farm waste and food waste is a debated topic. This could create synergies between farming and urban areas, and increase the uptake of agricultural waste and residues. Banks *et al.* (2011) proposed centralised treatment centres where pasteurisation of food waste takes place before it is sent to farms for co-digestion with dairy cow slurry. Dennehy *et al.* (2017) applied stochastic modelling, via Monte Carlo simulations, to evaluate the financial viability of on farm mono-digestion of pig manure, and co-digestion of pig manure and segregated food waste, with variable incentives, gate fees, annual amount of food waste received, and digestate disposal costs.

Lauer *et al.* (2018) used a non-linear optimization tool to investigate the viability of AD on dairy farms in Idaho in the USA. They showed that AD is viable on dairy farms with more than 3,000 cows, which is equivalent to circa 45 % of total available manure potential in Idaho. The structure of the dairy industry in the USA allows a considerable number of large dairy farms, unlike that which occurs in Europe.

Blumenstein *et al.* (2016) compared the financial viability of organic biogas systems versus conventional biogas systems. Organic biogas systems rely merely on substrates that are complementary with food production such as grass and clover grass. They argued that despite the financial advantage of conventional biogas systems over organic biogas systems, the latter brings about wider environmental benefits due to enhanced bio-fertiliser production and synergistic effects with food production.

Walla *et al.* (2008) highlighted that government financial support to biogas production distorts the economies of scale of biogas production. In fact, they showed that the lowest cost of biogas and electricity production from AD plants in Austria fed only with maize, lied between 500 and 1,000 kWe, depending on the availability of maize in the proximity of the plant. However, this contrasts with what happened in practice, where plants with capacities lower than 250 kWe were the most profitable due to grants and higher tariffs for electricity generation.

Skovsgaard *et al.* (2017) expanded on the work of Walla *et al.* (2008) to investigate economies of scale of biogas production from mono-digestion of manures, and co-digestion of manures with sugar beet, in centralised AD plants in Denmark. They concluded that economies of scale occurred with increasing plant capacity of mono-digestion of manures, whilst this was not the case for co-digestion of manures with sugar beet, due to transportation costs. This highlights the need for flexible and short supply chains of co-substrates, to offset risks associated with price fluctuations and variable substrate availability.

The relative benefits of centralised versus decentralised biogas networks supply is a debated topic in organic waste management and treatment. The degree of decentralisation or centralisation depends on the density of treatment plants in a region and leads to three possible biogas supply networks: centralised, distributed, and on-farm systems. In Germany and Sweden the majority of biogas plants are part of more distributed networks (Mata-Alvarez *et al.*, 2014). In Denmark the biogas industry has experienced a shift from biogas plants owned by farmers to more centralised plants, with increasing capacity, owned by private companies who collect slurry from farmers and deliver digestate back to them (Franco *et al.*, 2015).

Patterson *et al.* (2011) showed that the centralised supply network had a small advantage over the distributed network approach across all LCA impact categories, until transportation requirements exceed 20-30 million tkm (tonne-kilometer) per year. This could be a cut-off point to indicate the need to switch from a centralised to a more distributed biogas supply infrastructure. The same authors indicated that 6,326 tonne $year^{-1}$ of feedstock was the minimum financially viable scale of a digester in the UK.

O'Shea *et al.* (2017) estimated that a decentralised network with AD plants installed on pig farms, and pipelines connecting them to the biogas end user, was the optimal configuration in terms of energy consumption and GHG emissions, compared to a centralised AD facility and associated road haulage of pig slurry.

2.9. Degradation efficiency of agricultural biogas plants

Three studies looked at the efficiency of agricultural biogas plants in one of the most important biogas markets in Europe, namely Germany and Sweden (FNR, 2010; Ruile *et al.*, 2015; Ahlberg-Eliasson *et al.*, 2017). They estimated the biodegradation efficiency by measuring the reduction in volatile solids. They achieved this by sampling each substrate in the feedstock mix and the digestate in the digester outlet, and post storage, at operational AD plants. Samples were analysed to measure primarily TS, VS and BMP, amongst other parameters. The operators of the plants provided the remaining operational data, namely volumes of tanks, digestion temperature, biogas throughput, and wet tonne per day of feedstocks.

In Germany Ruile *et al.* (2015) examined 21 biogas plants of different sizes and configurations. They showed that feedstock composition and HRT had a huge impact on the VS degradation efficiency, whilst single-stage and multi-stage systems did not show significant differences. AD plants mainly fed with slurries and manures returned the lowest VS destruction rate, at between 20 and 30 % of VS added to the digester, due to operating at HRTs lower than 30 days. By contrast, AD plants fed with a mix of livestock waste and energy crops, or mono-digestion of crops, showed higher efficiencies at between 70 to 85 % due to operating at higher HRTs, ranging from 36 up to 200 days. They argued that HRT of 80-100 days were enough to achieve the target VS degradation efficiency measured in this study.

In Sweden Ahlberg-Eliasson *et al.* (2017) evaluated the performance of 27 farm-scale biogas plants. They found that OLRs and HRTs of the plants range, respectively, between 1.0 and 3.2 kg VS m^{-3} d^{-1} and 23 and 63 days, leading to gas yields between 120 and 478 m^3 CH_4 per tonne of VS, and degrees of biodegradation varying from 23 to 75%. They confirmed the findings of Ruile *et al.* (2015), that the degree of degradation improveed with increasing HRTs for plants that co-digest, and feedstock mixtures based on pig slurry or manure. However, HRTs and biogas yields were lower than the study on German plants, due to higher overall proportion of manures in the feedstock mix on a wet weight basis.

2.10. Life Cycle Assessment of AD

LCA is one of the standard tools (Silgram *et al.*, 2001) used in environmental management to analyse the environmental impact of processes and products. Figure 2-2 shows the dramatic increase in the number of publications on LCA applied to biogas systems up to 2018. This figure is the result of a search on Scopus with key words “LCA and Biogas” resulting in more than 500 studies between 2000 and 2018.

The estimation of the overall environmental impact in LCA studies is based on mass and energy balances associated with physical flows in and out of the system boundaries over the lifetime of the product from the production of raw materials to the disposal stage. The impact refers to the Functional Unit (FU), which depends on the focus of the study.

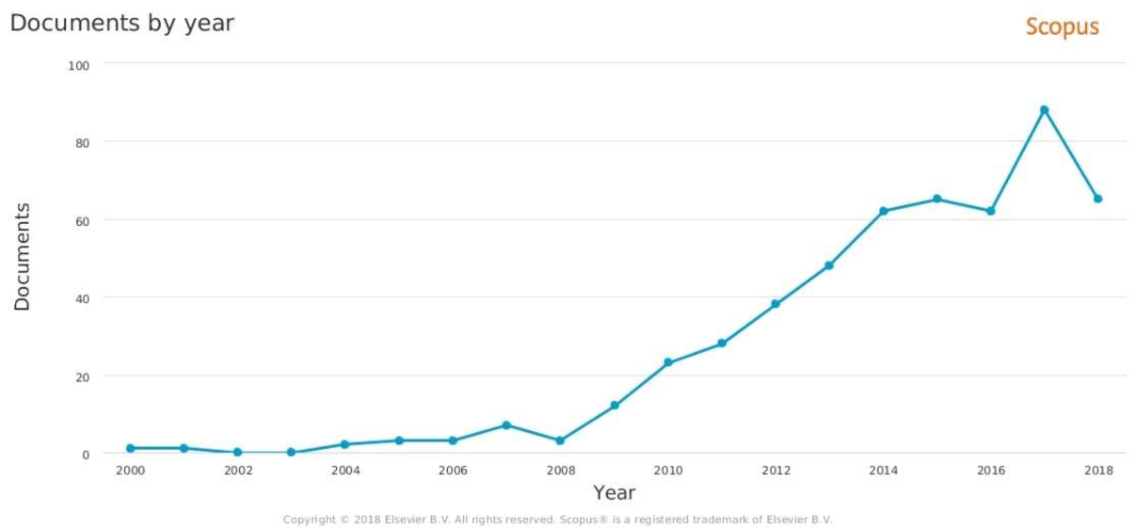


Figure 2-2: Number of papers published in LCA of biogas systems by year between 2000 and 2018 (retrieved from https://www.scopus.com/)

A defined unit of output, for instance 1 MJ of heat or electricity produced, is used to explore the optimal use of a given feedstock to achieve the provision of a service. On the other hand, a defined unit of one wet or dry tonne of feedstock mix is used to compare the performance of various feedstocks. The attribution of the impacts to a defined unit of agricultural land is a good indicator of land use efficiency for energy crops (Cherubini *et al.*, 2011).

Representativeness, consistency, and quality assurance of life cycle inventory data are all crucial in LCA. Databases, such as Ecoinvent (Frischknecht *et al.*, 2005), and literature values are adopted for “background” processes that are not affected by the decision maker. Specific primary data should be collected directly from operational biogas plants via monitoring data (Lansche *et al.*, 2012; Bacenetti *et al.*, 2013; Fuchs *et al.*, 2013) or surveys and interviews (Styles *et al.*, 2016).

Emissions into air, water and soil are classified into impact categories depending on the methodology adopted, for instance ReCiPe (Goedkoop *et al.*, 2008) is widely used in LCA literature. The most relevant impact categories for LCA studies on anaerobic digestion are climate change, terrestrial acidification, marine and freshwater eutrophication, and fossil fuel depletion.

LCA studies are divided into Attributional LCA (ALCA) and Consequential LCA (CLCA). ALCA accounts for mass and energy flows across the system boundaries, but it ignores the impacts from processes replaced by the system itself. ALCAs are linear, steady state models based on average data. ALCA is useful when the purpose is to identify hotspots in the process under examination, to identify improvements in environmental performance (Finnveden *et al.*, 2009)

Consequential LCA looks at the overall impact that a specific process can have by including the consequences of avoided processes or substituted products. LCA studies use system enlargement to include environmental impacts from processes replaced by the biogas system within the boundaries. These impacts are then subtracted from the total environmental impact of the biogas system. System enlargement removes the need of the allocation of the overall impact among biogas inputs / outputs.

Economic models are commonly used in CLCA of bioenergy systems where the implications on direct and indirect land use change (Finnveden *et al.*, 2009), and when food supply chains are considerable (Marvuglia *et al.*, 2013). Direct and indirect land use impacts arising from the replacement of substrates used in AD can have important consequences on the results of comparative LCA studies of bioenergy systems (De Vries *et al.*, 2012b).

Uncertainty quantification is an essential part of LCA studies. Clavreul *et al.* (2012) reviewed uncertainty analysis for LCA studies in waste management systems. They argued that a sensitivity analysis should start from a perturbation analysis, which means changing all parameters independently and within sensible ranges, to compute the respective sensitivity coefficients, or a scenario analysis, where parameters are changed according to a set of pre-defined scenarios. Approaches based on Monte Carlo simulations are recommended to propagate parameter uncertainty (Clavreul *et al.*, 2012).

Meta-analysis of LCA studies are challenging because of the heterogeneity in the life cycle inventory data, the definition of the system boundaries, reference scenario(s), and various assumptions. Figure 2-3 illustrates an example of the inherent heterogeneity of LCA studies for the case of mono-digestion of pig slurry.

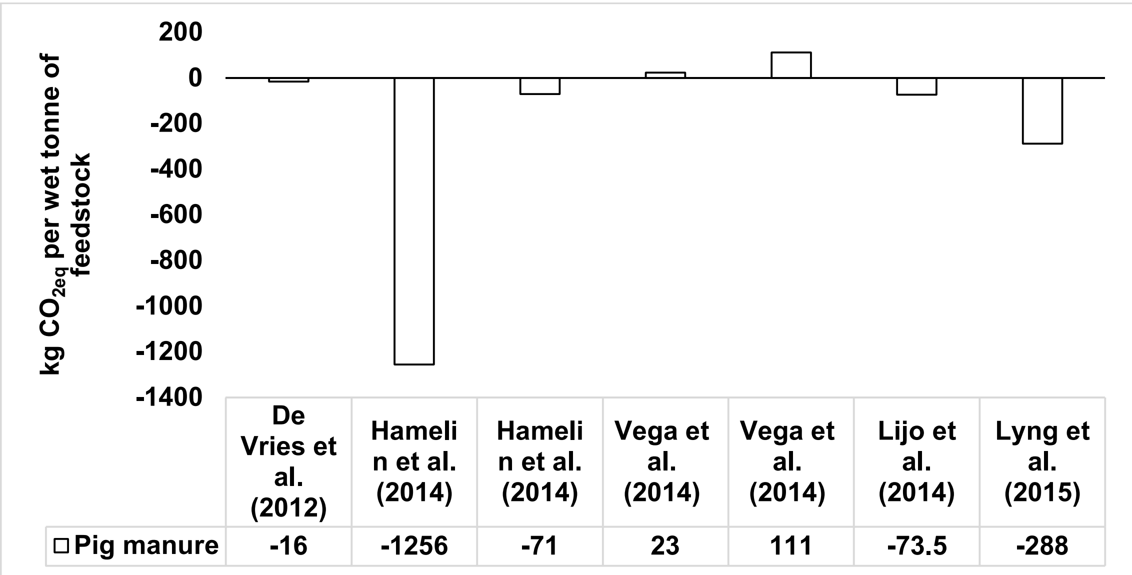


Figure 2-3: Comparative analysis of LCA studies on mono-digestion of pig slurry to show the impact of system definition and assumptions on results.

This heterogeneity is due to numerous assumptions on various aspects:

- Direct land use change (DLUC) and indirect land use change (ILUC) due to cultivation of energy crops on arable land or grassland (Hamelin et al., 2014).
- The "zero burden assumption" (Ekvall *et al.*, 2007) entails that a feedstock does not carry over the impact of upstream processes.
- The assumed nutrient replacement value of digestate spread to land.
- The impact of cultivation, harvesting and transport of energy crops.
- The majority of the LCA studies on bioenergy systems neglect soil C sequestration (Hamelin *et al.*, 2014), and biogenic CO_2 emissions from biomass combustion, which are assumed to be climate neutral. This means that the CO_2 emissions from combustion are assumed to offset the CO_2 absorbed during plant growth (Croxatto Vega *et al.*, 2014).
- Methane losses range between 1 % up to 15 % (Berglund *et al.*, 2006).
- Assumed transportation distances for feedstocks and digestate (Poeschl *et al.*, 2012).
- The impact of capital goods and infrastructure of the biogas plants.
- Type of digestion process (wet or dry), temperature, type of reactor (i.e. CSTR, batch etc), DS content of feedstock mix.
- Avoided processes (heat, electricity, transport fuel) and the reference scenario(s).

Primary Energy Input Output (PEIO) coefficients indicate the ratio between the energy inputs to produce biogas and the energy output from biogas. This ratio must be lower than 1 to make sure that energy output exceeds input. PEIO ranges from 12 % for grease separator sludge to 40 % for ley crops (Berglund *et al.*, 2006). The energy balance turns negative if manure and straw transportation exceeds respectively 200 km and 240 km (Berglund and Börjesson, 2006). Poeschl *et al.* (2012) found that the PEIO ratio varied between 10.5 % for straw and 64 % for cattle manure, with the energy balance turning negative for manure transport distances above 22 km.

Salter *et al.* (2009) estimated the PEIO for various energy crops, referring to one hectare of land as a term for comparison, and concluded that crops with low yields and high energy inputs for cultivation showed the lowest energy ratio. Miscanthus is an interesting crop for bioenergy production with low production inputs, high yields, soil carbon sequestration, and related ecosystem benefits (Styles *et al.*, 2015a). Blengini *et al.* (2011) confirmed this trend finding that Miscanthus and sorghum showed the lowest Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP) per MJ of energy output when compared to maize.

The PEIO of co-digestion of cattle manure with energy crops, straw and other waste streams, such as food waste and slaughterhouse waste, varied between 45.6 and 48.6 % for small scale biogas plants (<500 kWel) and between 34.1 and 55 % for large biogas plants (>=500 kWel) (Pöschl *et al.*, 2010). Significant improvements in the PEIO could be achieved with enhancing heat recovery.

Berglund *et al.* (2006) demonstrated that it was hard to determine average life cycle emissions, even for biogas systems delivering the same energy service, since each biogas system is unique. However, there was a clear trend showing that waste feedstocks, such as manures or crop residues, had a comparative advantage over energy crops in terms of life cycle environmental impacts (Börjesson *et al.*, 2007). Numerous LCA studies in the literature corroborated these findings (De Vries *et al.*, 2012b; Lansche *et al.*, 2012; Croxatto Vega *et al.*, 2014; Hamelin *et al.*, 2014; Lijó *et al.*, 2014; Styles *et al.*, 2015a).

LCA results are sensitive to fugitive methane emissions and whether digestate stores are covered or not (Mezzullo *et al.*, 2013; Whiting *et al.*, 2014; Styles *et al.*, 2015a; Styles *et al.*, 2015b), recovery of the residual biogas from storage tank (Poeschl *et al.*, 2012; Boulamanti *et al.*, 2013), digestate spreading methods (Whiting *et al.*, 2014; Styles *et al.*, 2015a; Styles *et al.*, 2015c), and the degree of utilization of the heat recovered from the co-generation unit (Bacenetti *et al.*, 2013). Most studies indicate that AD increases the risks of AP and EP due to ammonia emissions during digestate storage and spreading to land (Lijó *et al.*, 2014; Whiting *et al.*, 2014; Lijó *et al.*, 2015; Styles *et al.*, 2015a).

Croxatto Vega *et al.* (2014) showed that LCA results depended on the alternative uses of the feedstocks used for AD. For instance, when straw was diverted from the fields, the largest CO_2 savings could be achieved. However, if it was diverted from incineration to produce electricity towards AD, it could give rise to an increase in GHG emissions (Börjesson *et al.*, 2007). This indicatesd that AD was more suitable to treat substrates with reduced LHV (Lower Heating Value) and DS content.

Styles *et al.* (2015a) argued that bioenergy policy should limit the utilization of energy crops in the feedstock mix to prevent international "carbon leakage", that could occur when maize or grass silage are diverted from animal fodder to bioenergy production. This is likely to trigger land use changes in the UK and elsewhere in international markets, to replace the production of animal fodder feed.

Styles *et al.* (2015a) came to the same conclusions for arable farms in the UK. However, they noted that short food-energy crop rotations on arable farms, allowing cultivation of maize as a break crop between spring barley and winter wheat, might offer an option to mitigate the impact associated with food displacement and indirect land use change. From Styles *et al.* (2016) and other studies it can be concluded that energy policy should incorporate the following key elements to improve the environmental profile of the UK biogas sector:

- Subsidies should emphasise the role of AD as a waste management solution for manures and other waste, rather just an opportunity for the production of renewable energy.
- Use of energy crops in the feedstock mix that give rise to direct and indirect land use change should be minimised. Sustainable crop rotations (Dale *et al.*, 2010) offer a solution to mitigate the impact of cultivation of energy crops, and provide ecosystem services at the same time.

- Uptake of small-scale manure-fed AD systems should be encouraged, since the associated environmental benefits would outweigh higher installation costs and lower energy outputs.

2.11. Gap Analysis

As a result of the literature review the following key points can be identified for investigation in relation to confirming the aims of this research.

To date, research has focused on resource mapping, quantification of biomass and energy potentials, and its application to serve a broad range of purposes. However, there is little knowledge on the quantification of the unutilized biomass potential from livestock waste, i.e. manures and slurries, for biogas production, and the infrastructure needed to utilize this waste via anaerobic digestion. A quantified understanding of this opportunity could provide government and policy makers with evidence that support is needed to boost the uptake of on farm AD, leading to greater sustainability and renewable energy production.

There is little awareness on the efficiency of agricultural biogas plants in the UK. Studies from Germany and Sweden have explored this topic in some detail, but there is nothing in the literature where such techniques are specifically applied to the UK situation. An analysis of this aspect is therefore an important component of any recommendations that might aim to increase the uptake of, and perhaps subsidy of, on farm AD systems.

Alongside this, an evaluation of the status of existing on farm AD installations from the experiences of operators and plant managers will be used to highlight practical barriers and opportunities to enhance future development of this circular economy approach to agricultural biosolid wastes.

2.12. Objectives

In order to deliver the high level aims of quantifying available agricultural bioresources in the UK for biogas production via AD systems, in relation to spatial availability and economic potential, the following specific objectives are set for this research:

1) Create a land use and manure resource management tool in GIS
2) Estimate the biomass arising from livestock waste that is potentially available to use for AD in England, via the development of a GIS analysis tool linked to Defra census data.
3) Quantify the latent biomass resources stemming from livestock waste by comparing the potential biomass resources and current consumption from operational biogas plants.
4) Identify the location and quantify the number and capacity of new small-scale on-farm biogas installations needed to meet hypothetical minimum policy targets of 25 and 50 % of biomass potential utilized via AD.
5) Create an Excel based biogas calculator to estimate the economic sustainability of biogas production via AD of available agricultural bioresource solids, in relation to the scale of operation, feedstock mixture, and geographical availability of feedstocks.
6) Design a questionnaire to collect operational and financial data from existing agricultural AD plants with input from biogas plant managers and operators. This data will be used to investigate the current status of on farm AD with respect to: feedstock mix utilized, transportation of biomass, digestate management, mineral fertiliser savings, parasitic load, heat usage, Capex and Opex.
7) Estimate the four parameters of the first order kinetic model of a CSTR reactor used in the biogas calculator via non-linear fitting curve in MATLAB®.
8) Evaluate the efficiency of agricultural biogas plants measured in terms of VS degradation.
9) Test the predictive capacity of the biogas production calculator against financial data gathered from the case studies in relation to: Capex and

Opex, mineral fertiliser savings, heat parasitic load (HPL), electric parasitic load (EPL).

Table 2-4 shows the chapter outline with an indication of the chapter where each objective is met.

Table 2-4: A visualisation of the chapter outline highlighting in which chapter each objective is met.

Objective	Chapter number
1	3
2 3 4	5
5	4
6 7 8 9	6

3. Development of a GIS based agricultural biomass resource evaluation tool.

This chapter describes the methodology implemented to create the GIS based database and tool that can be used to link waste biomass potential and current consumption of biomass for biogas production for policy scenario evaluation. This tool then underlies the spatial analysis to evaluate the implications of hypothetical new renewable energy policies in terms of extent of deployment and scales of operations. The creation of the GIS based database and tool was achieved in six main steps:

1. Data collection and Resource Assessment: this analysis starts with a quantitative assessment of biomass available for anaerobic digestion at the national, county and Local Authority levels. Data was collected for livestock waste (manure and slurry) and presented as mass of substrate (wet tonnes) and potential biogas (m^3).
2. Demand Assessment: the evaluation of the current consumption arising from biogas plants was based on data provided by the NNFCC Ltd. (2018). Total feedstock demand waas broken down by mass per feedstock category.
3. Land Use Dataset Development: here the land use information from the UK Land Cover Map (LCM) was migrated onto a 1 km^2 grid and aligned with the land use information provided by Defra at the Local Authority scale.
4. Areal Interpolation: variables relative to volumes of substrate (wet tonnes) and potential biogas (m^3) per feedstock type were scaled to a smaller level (1 km^2 grid) using the land use dataset as ancillary information.
5. Model evaluation: the land use dataset was evaluated against the Defra land use dataset available to the public at 5 km^2 spatial resolution.
6. Location-allocation algorithm: the P-median problem was applied to a small region in the South West of England to identify the minimum number

of new facilities to meet hypothetical policy targets in presence of competitors.

3.1. Data Collection and Resources Assessment

Data on land use and livestock distribution comes from the 2016 June Agricultural Survey (JAS) published by DEFRA (2017) in England. The data were mapped using QGIS at county and local authority level while data manipulation and analysis were carried out in MATLAB®. At the county level the data provides information on use of arable land per hectare, by crop type and number of livestock by group (i.e. cattle, pig, poultry, sheep, goats, horses, and farmed deer), animal category (e.g. dairy or beef cattle) and by age. Defra has provided a breakdown of land use, by hectare, for maize production into maize as grain product, energy crop, or animal fodder.

3.1.1. Quantification of technical biomass potential arising from livestock waste

The method for livestock waste quantification was based on the MANURE-GIS national inventory of livestock manure from DEFRA (ADAS, 2008). Their assumptions on annual excreta production by livestock group, category and age, along with excreta apportionment by time of the year and type of manure, i.e. either slurry or Farm Yard Manure (FYM), were used as a means to quantity livestock waste stored during a year, and therefore deemed to be usable for AD. The inventory uses typical values of excreta production in kg head^{-1} day^{-1} by livestock type and category.

The technical potential refers to slurries and manures that are stored and not immediately spread to land, hence available to use in AD systems. This biomass was assumed to be completely available for anaerobic digestion. This quantity was calculated by Equation 3-1:

$$TBP_{manure} = Number\ of\ heads \times Excreta\ production \times Time\ in\ house \times Fraction\ stored$$

Equation 3-1

Where:

- Number of heads is the number of animals in each livestock category at the County and Local Authority level. These variables are directly given in the agricultural survey by Defra.
- Excreta production is the typical excreta production in wet tonne y^{-1}. Values used in the calculations are given in Appendix C.
- Time in house represents the percentage of the time in a year that the specific livestock category spends in housing. Values used in the calculations are given in Appendix C.
- Fraction stored is the biomass that is stored and not spread immediately to land. This quantity is divided into four fractions: slurry that is stored, slurry that is spread fresh, FYM that is stored and FYM that is spread fresh. Values used in the calculations are given in Appendix C.

3.1.2. Quantification of technical biomass potential arising from cereal straw

Straw is a residue from growing and harvesting cereals. When cereals are harvested, the stubble is usually left on the field to replenish the organic carbon content of soil, whereas straw is collected and stored. In the UK in 2016 75% of the total straw production was required for animal bedding and 8% was required for other uses including power generation. This left approximately 17% of the total straw production available as spare feedstock (Defra, 2016).

Straw yields are typically 3.5 tonnes ha^{-1} for wheat and oats and 2.75 tonnes ha^{-1} for barley and oilseed rape. If these values are compared with the corresponding typical grain yields for England in 2016, which are 7.9 tonnes per hectare for wheat, 5.6 for oats, 6.4 for barley and 3.1 for oilseed rapethenapproximately 0.5 tonnes of straw per tonne of cereal grain harvested is available (Defra, 2016). Hence, the straw available for use in AD is calculated via Equation 3-2:

$$TBP_{straw} = Straw\ Production - Straw\ for\ animal\ bedding\ and\ feed - Straw\ for\ other\ uses$$

Equation 3-2

Where straw production is calculated as Equation 3-3:

$$Straw\ Production = \sum_{i=1}^{n} Cereal_i(ha) \times Cereal\ Grain\ Yield_i\ (tonne\ ha^{-1}) \times 0.5$$

Equation 3-3

Typical figures for the demand of straw for animal bedding and feed by livestock group are shown in Table 3-1 derived from the BiomassPolicies project (European Commission, 2016) with demand of straw for cattle adjusted to align it with the UK context.

Table 3-1: Estimates of quantity of straw used for bedding by livestock group

Livestock Group	Straw Production in kg per day per head
Cattle	3.0
Sheep and Goats	0.1
Pigs	0.5
Horses	1.5

Approximately 8 % of the total annual production of straw in 2016 was allocated to other uses other than animal bedding and feed (Defra, 2016). This value was derived from the figure at the national level and was assumed appropriate as no further information was found at smaller length scales.

3.1.3. Estimation of the methane and energy production potential

Defra statistics are aggregated according to the hierarchical representation of Eurostat Statistical Geographies, which are in descending order of scale NUTS 1, 2 (county level) and 3 (Local Authority level). Hence, a Local Authority is a subset of a county. Table 3-2 summarizes the types of manures and slurries quantified at the county and local authority level. The biogas potential in terms of $m^3\ y^{-1}$ of methane and energy in terms of $MJ\ y^{-1}$ are calculated for each type of manure as per Equation 3-4 and Equation 3-5:

$$APPM = TBP_{manure} \times DS \times VS \times BMP_o$$

Equation 3-4

$$APPE = APPM \times LHV_{CH}$$

Equation 3-5

Where:

- *DS* is Dry Solids as a percentage of wet weight.
- *VS* – Volatile Solids as a percentage of DS.
- BMP_o is the ultimate bio-methane potential. Reference values are taken from the online KTBL database, Defra fertiliser manual (2010) and other references from the literature as shown in Table 3-2.
- LHV_{CH4} is the low heating value of methane, equal to 37.78 MJ m^{-3} (Wellinger *et al.*, 2013).

Table 3-2: Parameters used to characterize livestock manures and slurries based on literature data. DS is dry solids expressed as percentage of wet weight. VS is volatile solids expressed as percentage of DS.

Type of manure	*DS* (%)	*VS* (%DS)	BMP_o (L kg VS^{-1})	References
Cattle slurry	8	90	181	(KTBL; Möller *et al.*, 2008; DEFRA, 2010)
Cattle FYM	25	84	209	(KTBL; Möller *et al.*, 2008; DEFRA, 2010)
Pig slurry	6	72	336	(KTBL; DEFRA, 2010)
Pig FYM	25	82	316	(Möller *et al.*, 2008; DEFRA, 2010)
Sheep FYM	25	77	151	(KTBL; DEFRA, 2010; Cu *et al.*, 2015)
Layer manure	35	80	198	(KTBL; DEFRA, 2010)
Litter	60	70	293	(KTBL; DEFRA, 2010)
Horse FYM	30	75	155	(DEFRA, 2010; Kafle *et al.*, 2016)
Goat FYM	43	79	159	(DEFRA, 2010; Kafle *et al.*, 2016)
Straw	91	96	195	(Möller *et al.*, 2008)

3.2. Demand Assessment

Data for the quantification of the current consumption of livestock waste from operational biogas plants in the UK and, for the purpose of this study, in England derived from NNFCC Ltd (2018). This Excel-based dataset includes the locations of all operational biogas plants at the end of 2017, and feedstock volumes broken down by type for each plant: manures and slurries, energy crops, food waste, crop waste, and other wastes. The data was converted into a shape file to show the location of plants as point features.

3.3. Land Use Dataset Development

The methodology builds on the approach of Comber *et al.* (2008), but takes a more direct approach to the problem. They used dasymetric mapping and a pycnophylactic interpolation technique to obtain a land use database starting from agricultural data at the parish level. They intersected the OS-Strategy Map with a 1 km^2 regular grid to make a first estimate of non-agricultural land use in each local authority. They then used an algorithm to refine these estimates until they matched the non-agricultural land reported in the June Agricultural Survey (JAS), using the UK Land Cover Map (LCM) (Morton *et al.*, 2011) as an upper bound constraint in each grid cell. The latter classifies land into 23 categories aggregated according to the criteria in Table 3-3.

Table 3-3: Aggregated Classes of the Land Cover Map of the UK according to Morton *et al.* (2011).

Class	Land use category
1	Broadleaf woodland
2	Coniferous woodland
3	Arable
4	Improved grassland
5 to 9	Semi-natural grassland
10 to 14	Mountain, heath, bog
15	Saltwater
16	Freshwater
17 to 21	Coastal
22 & 23	Built-up areas and gardens

In this work the UK LCM was used directly as the best first estimate of arable land and grassland (Classes 3 and 4 in Table 3-3) within each Local Authority. The 1 km^2 regular grid was intersected with the LCM to ensure that each grid cell inherits land use information. Each grid cell was then allocated to a local authority if its centroid falls within the local authority boundaries. The hectares of arable land and grassland in each grid cell were summed to yield a first estimate of the total arable land and grassland in the Local Authority.

Arable land in the JAS was defined as the sum of cereals, arable crops (excluding cereals), fruit and vegetables. Total grassland is the sum of temporary grass (sown in the last 5 years), grass over 5 years old, and sole rights rough grazing land. The information on agricultural land use provided by the JAS at the LA level is somewhat representative of land use changes in England over time, since the release of the UK Land Cover Map. Therefore, an algorithm was implemented to ensure that arable land and grassland derived from the LCM converged to the corresponding arable land and grassland data from the JAS. The algorithm was adapted from Comber *et al.* (2008) to accommodate the new implementation.

Figure 3-1 illustrates the logic underpinning the algorithm. It starts by calculating the difference between the variable named *Arable2(i)* in Equation 3-6, which is the agricultural land area in hectares according to LCM, and the variable $Arable1_i$, which is agricultural land from the JAS for each local authority. This difference is then divided by the total number of centroids within the local authority to find a scalar that is applied evenly to scale up or down the arable land area in each grid cell.

$$Scalar = \frac{|Arable2_i - Arable1_i|}{n_i}$$

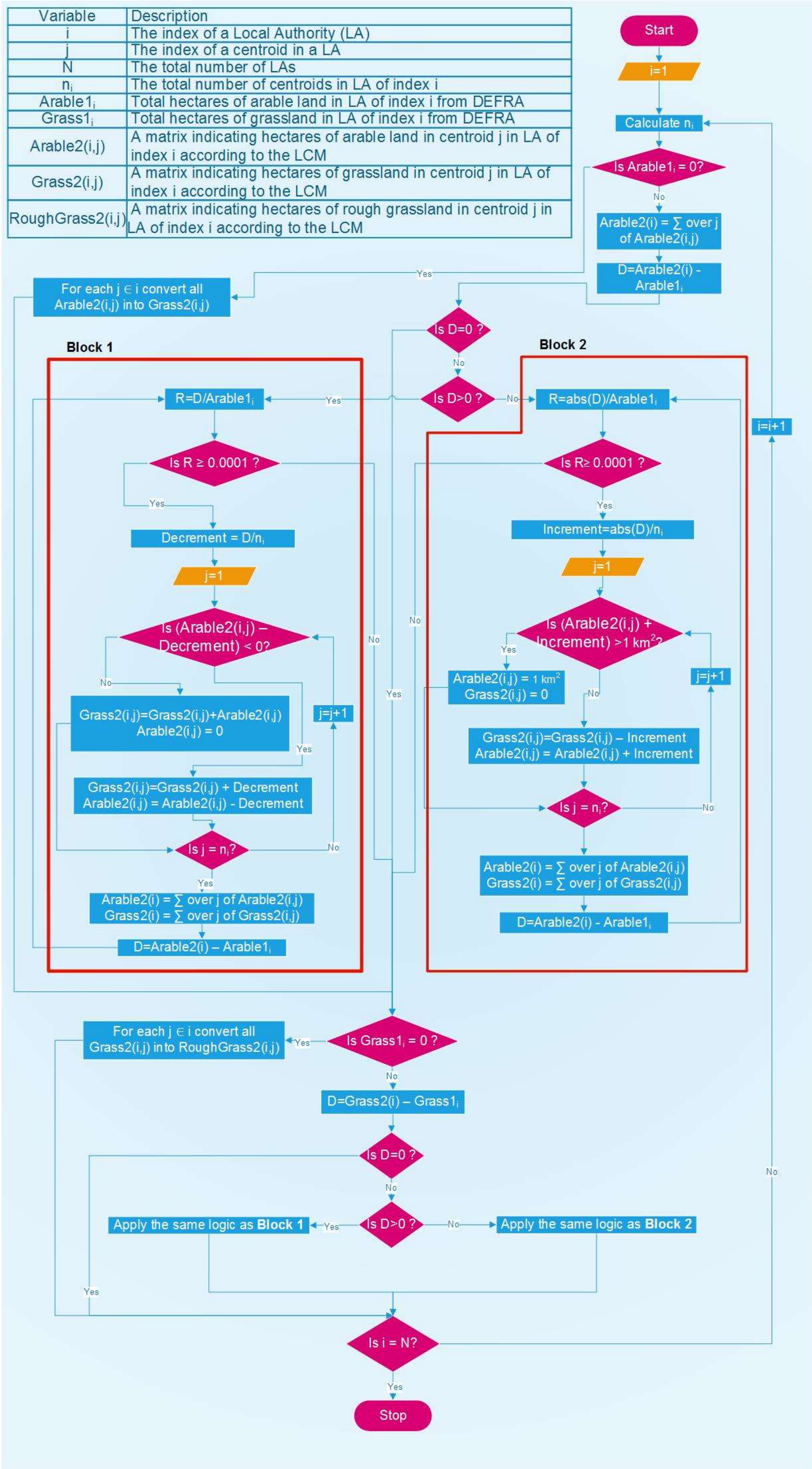
Equation 3-6

In each grid cell the adjustment in arable land area (Class 3) is mirrored by an equivalent change in improved grassland area (Class 4) to ensure that the total area of each grid cell is conserved. At the end of this step, the new total arable land area in the local authority is calculated. Finally, it is compared with the agricultural land area according to the JAS to check for convergence via Equation 3-7:

$$Convergence = \frac{|Arable2_i - Arable1_i|}{Arable1_i} \leq 10^{-4}$$

Equation 3-7

Iterations continue until convergence criteria is met. The same logic applies to grassland land use class. However in this case, the reallocation of hectares of grassland in each grid cell to align it with the total area of grassland reported in the JAS draws on land classified as improved grassland (4), rough grassland (Class 5) and then other land use classes in “semi-natural grassland” in the following order until convergence: neutral grassland (Class 6), calcareous grassland (Class 7), acid grassland (Class 8) and then fen, marsh and swamp (Class 9).



Variable	Description
i	The index of a Local Authority (LA)
j	The index of a centroid in a LA
N	The total number of LAs
n_i	The total number of centroids in LA of index i
$Arable1_i$	Total hectares of arable land in LA of index i from DEFRA
$Grass1_i$	Total hectares of grassland in LA of index i from DEFRA
Arable2(i,j)	A matrix indicating hectares of arable land in centroid j in LA of index i according to the LCM
Grass2(i,j)	A matrix indicating hectares of grassland in centroid j in LA of index i according to the LCM
RoughGrass2(i,j)	A matrix indicating hectares of rough grassland in centroid j in LA of index i according to the LCM

Figure 3-1: Flowchart of the algorithm developed to align the Land Cover Map with the Defra agricultural survey.

3.4. Areal Interpolation

Each variable in the dataset at the Local Authority (LA) level can be conceptualized in mathematical terms as a function: $z = f(x, y)$, where z is the value of the variable and x and y are the geographical coordinates. Variable z changes from one LA to another but it is constant within the same local authority. However, if additional information is available on the properties of the function within a local authority then it is possible to estimate the value of z at smaller scales. In the scientific literature this is regarded as the areal interpolation problem (Goodchild *et al.*, 1993), aiming at transferring variable z from source zones, i.e. local authorities, to target zones, i.e. smaller areas.

The integrated LCM and Defra JAS land use dataset developed here was then used as ancillary information to transfer variables in Table 3-2 from the source zones, i.e. Local Authorities, to target zones, i.e. 1 km^2 grid cells. The coarse spatial scale (i.e., counties and Local Authorities) of the original dataset and lack of information on farms locations within the source zones, led to a pro-rata allocation of slurries and manures based on the fraction of arable or grassland in each grid cell. The criteria to create density maps for each variable involved the allocation of livestock waste from grazing animals and animals housed all year round respectively to grassland and arable land as explained below (ADAS, 2010):

- Slurries and FYMs from grazing animals (i.e. cattle, sheep, goats, horses, deer) were allocated to grassland.
- Slurries, FYMs from pigs and poultry ere allocated to arable land.
- Straw was allocated to arable land.

3.5. Model evaluation

Defra provides a land use database from the agricultural census of 2010 for public use, with a spatial resolution of 5 km^2. This dataset was used as a reference to test the predictions of the model developed in this study. There was a mismatch in the spatial resolution of the two models. Therefore this model was superimposed on the Defra model to allocate all centroids of 1 km^2 grid cell falling within the 5 km^2 grid cell. Variables associated with arable land and grassland at 1 km^2 grid were aggregated at the same scale as the Defra public dataset for comparison. RMSE between the Defra model and the model prediction was calculated according to Equation 3-8 (Comber *et al.*, 2008):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{(x_i - y_i)}{x_i}\right)^2}{N}}$$

Equation 3-8

Where x_i is the model prediction, y_i is the corresponding value from Defra and N is the number of points. Table 3-4 shows RMSE and R^2 correlation coefficients for arable and grass land.

Table 3-4: Results from the model validation against the public Defra dataset at 5 km2 spatial resolution

Land type	*RMSE*	R^2
Arable land	11.16	0.80
Grassland	2.07	0.65

Figure 3-2 and Figure 3-3 illustrate the correlation between the model and the Defra data. Figures show linear correlation between the model and Defra data for arable land with R^2 of about 0.8. This correlation is weaker for grassland even though the *RMSE* is improved compared to arable land. The spatial mismatch between the 1 km^2 grid and the 5 km^2 grid and the allocation methodology used could in part explain the outliers.

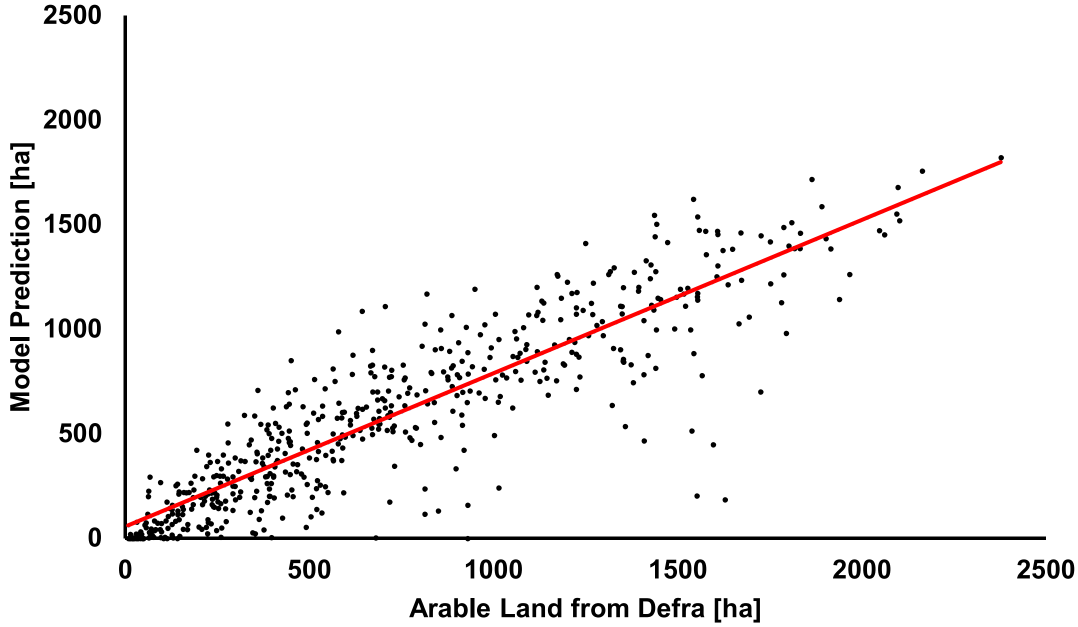


Figure 3-2: Correlation between arable land area from the DEFRA dataset and the model prediction at 5 km^2.

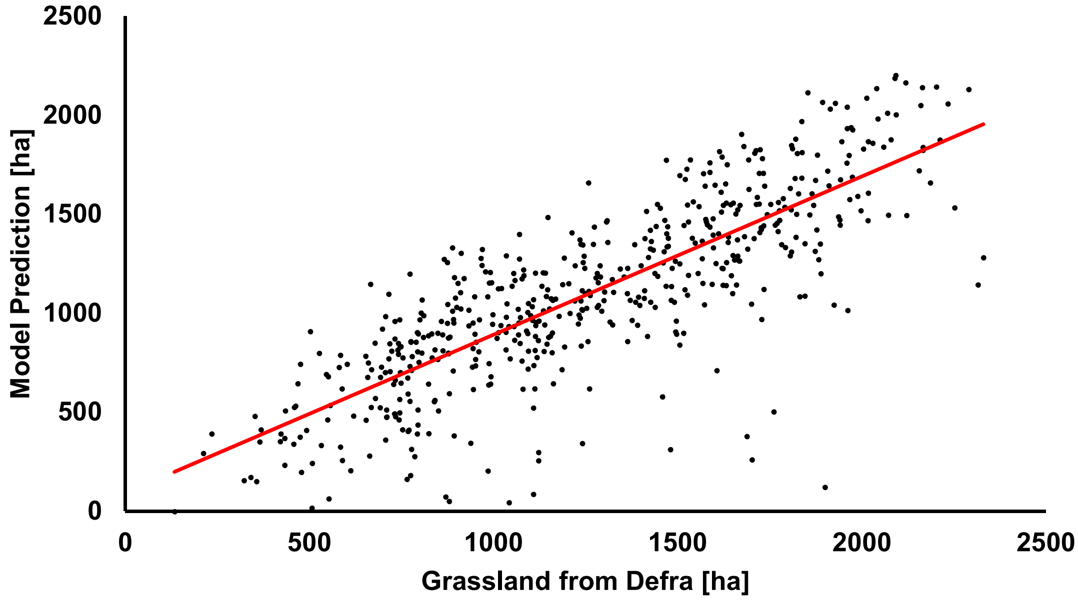


Figure 3-3: Correlation between grassland area from the DEFRA dataset and the model prediction at 5 km^2.

3.6. Location-allocation algorithm

Figure 3-4 shows the area under investigation comprising all catchments under Wessex Water jurisdiction located in the South West of England. The choice of this area as a case study was arbitrary in a way that enabled illustration of the application of spatial analysis techniques to investigate the implications of environmental policies requiring enhanced manures and slurries uptake in AD plants. Figure 3-4 also displays the locations of operational agricultural biogas plants in England, Wales and Scotland at the end of 2017. The agricultural biogas plants were representative of installations whose feedstock mixture was mostly composed of livestock waste, energy crops and crop residues.

The green dots in Figure 3-4 are possible candidate locations for the installation of new AD facilities. They correspond to all population centroids (ONS, 2017) that are within 1 km^2 grid cells of the land use dataset developed in this study having more than 50 % of arable land. This initial screening was needed to reduce the size of the pool of candidate locations to ease computations. As a result, 683 candidate locations were selected after this initial screening. The road network dataset was derived from the OS MasterMap®.

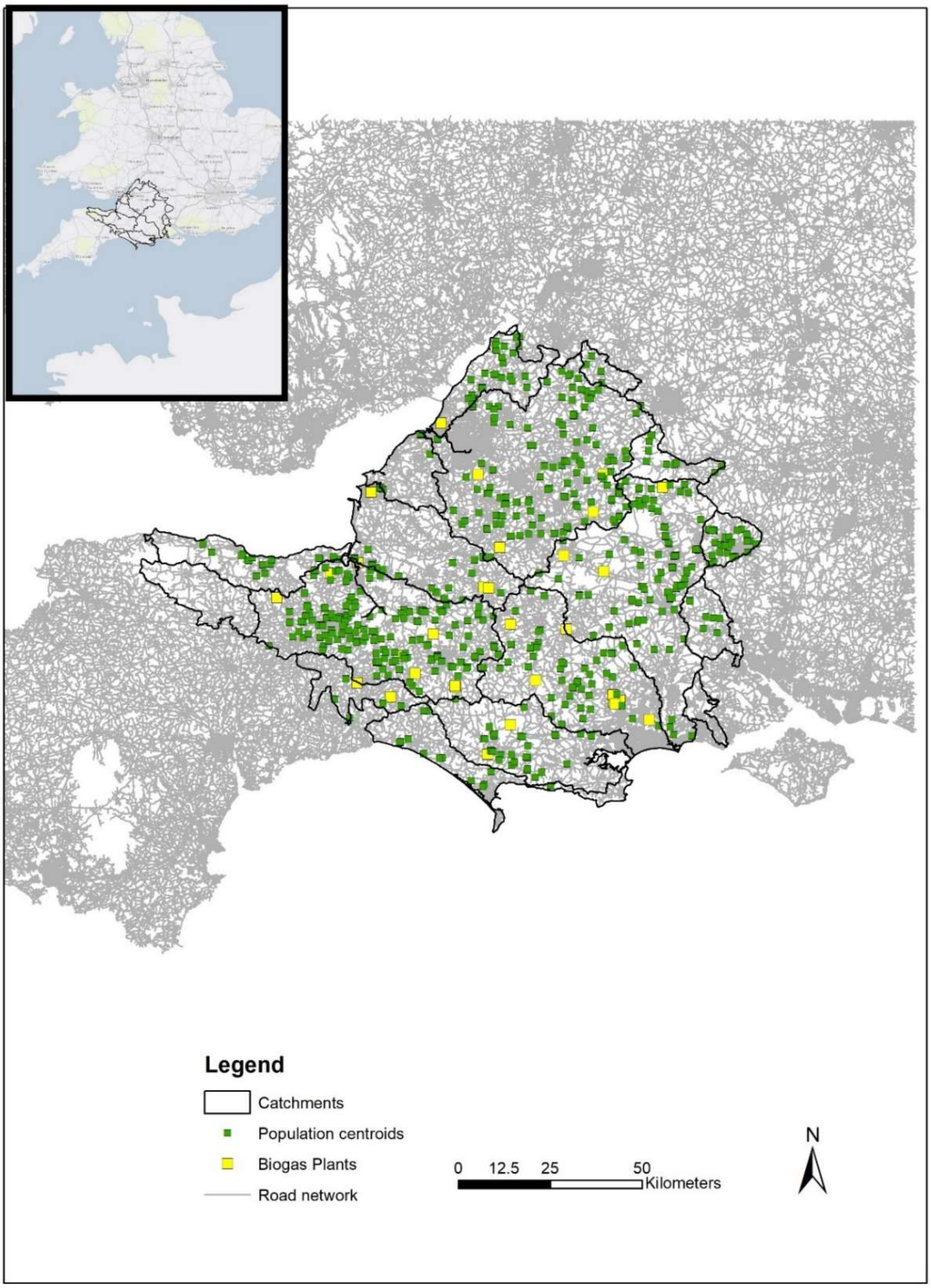


Figure 3-4: Map of the Wessex Water region. The area outlined with black solid lines represents the boundaries of the catchments that are the focus of this study. Yellow dots represent locations of agricultural biogas plants, green dots are population centroids.

The location-allocation algorithm was based on the classic *p*-median problem. Given a total number of candidate facilities *n*, the optimization problem looks for a subset *p* of *n* (*p* < *n*) such that the following function is minimized (Owen *et al.*, 1998):

$$Minimize \sum_i \sum_j h_i d_{ij} Y_{ij}$$

Equation 3-9

Where:

- i is the index of demand node
- j is the index of the potential facility location
- h_i is the demand at node i
- $d_{i,j}$ is the distance between demand node i and potential facility location j
- $Y_{i,j}$ is the decision variable associated with demand that can be either 1, if demand node i is assigned to potential facility location j, or 0 otherwise.

Equation 3-9 is subject to the following constraints:

$$\sum_j X_j = p \ (1)$$

$$\sum_j Y_{i,j} = 1 \ \forall i \ (2)$$

$$Y_{i,j} - X_j \leq 0 \ \forall i, j \ (3)$$

$$X_j \in \{0,1\} \ \forall j \ (4)$$

$$Y_{i,j} \in \{0,1\} \ \forall i, j \ (5)$$

Where:

- X_j is the decision variable associated with potential facility locations that can be either 1, if potential facility location j is chosen, or 0 otherwise.

- Constraint (1) states that the sum of all chosen locations must equal *p.*
- Constraint (2) defines that each demand point must be allocated to only one facility.
- Constraint (3) states that demand points that are allocated to chosen facilities are assigned 1 otherwise 0.
- Constraint (4) and (5) set decision variables to either zero or one.

The *p*-median problem is classified as NP-hard problem (Owen and Daskin, 1998), implying that it is impossible to search in the whole domain space since the number of all possible combinations of subsets of size *p* within *n*, given by Equation 3-10, is huge even for small *n* (Comber *et al.*, 2015). Heuristic approaches such as Teitz *et al.* (1968) have been developed to solve these types of problems.

$$\binom{n}{p} = \frac{n!}{p! \times (n-p)!}$$

Equation 3-10

The type of location-allocation problem in the network analyst toolbox in ArcGIS that defines the minimum target share to achieve in the presence of competitors was applied. This aims to find the minimum number of facilities that minimize the demand-weighted travel distance and, at the same time, meet a pre-defined target market share in presence of competition from existing facilities. The target share was the percentage of total demand of manures and slurries in the region. The search for demand points was limited to those lying within a cut off distance of 5 km from each candidate facility.

3.7. Conclusions

This study set out to quantify the biomass technical potential arising from livestock waste, namely manures and slurries, available in England. The approach adopted to create the GIS based model was based on a methodology that has been widely validated in the literature for biomass resource mapping. This research built on it to meet the objectives set at the beginning of this chapter.

The methodology presented here in this chapter to create the GIS tool is a slight variation of the methodological approach described in Comber *et al.* (2008). The underlying land use map derived from the Land Cover Map of the UK that was released in 2009 (Morton *et al.*, 2011). Given the inherent uncertainty associated with the spatial allocation of various groups of livestock to arable land and grassland, the accuracy of the land use reference dataset was not of paramount importance.

Therefore, the accuracy of the Land Cover Map of the UK in identifying hectares of arable and grassland sufficed. The use of an updated land use dataset would have probably led to a more accurate quantification of hectares of arable land and grassland without, however, reducing the uncertainty in livestock allocation.

The updated information on land use derived directly from the agricultural survey run by Defra on a regular basis. In fact, the methodology implemented in this study aimed to align the land use reference dataset from LCM of the UK with the corresponding land use information from Defra at the Local Authority level.

The biomass resource management tool can be applied to answer research questions concerning the quantification and efficient use of these resources to serve various needs, for instance in this case renewable energy production and organic fertilizer management.

In Chapter 5 this tool will be applied to quantify the biomass from livestock waste available for AD and identify optimal locations to utilize these resources under the hypothetical scenario of environmental policy setting out minimum targets for the utilization of this biomass via AD.

4. An economic evaluation tool for AD biogas viability.

This chapter presents the methodology created to develop the Excel-based biogas calculator to evaluate the viability of agricultural biogas plants. The aim was to develop a detailed application tool capable of sizing and costing each unit of the biogas plant based on realistic data gathered directly from technology suppliers and biogas plant managers. Figure 4-1 shows the full flowchart of a typical medium to big scale agricultural biogas plant. The same flowchart can be greatly simplified for small scale on farm AD mainly treating manures and slurries.

The tool created enabled the assessment of mono-digestion of manures and co-digestion of manures with crops, crop residues and other waste. The total wet tonne per annum of each type of feedstock in the mix was the input to the biogas calculator. This is composed of the following main sections:

- Feed characterization including calculation of the dilution if required
- Sizing of main digester and storage tank
- Estimation of biogas production
- Assessment of the heat and electric parasitic loads
- Assessment of the financial fertiliser value
- Estimation of Capex and Opex
- Financial analysis

The dataset used to characterize the most common feedstocks utilized at agricultural biogas plants is presented in Appendix A.12.

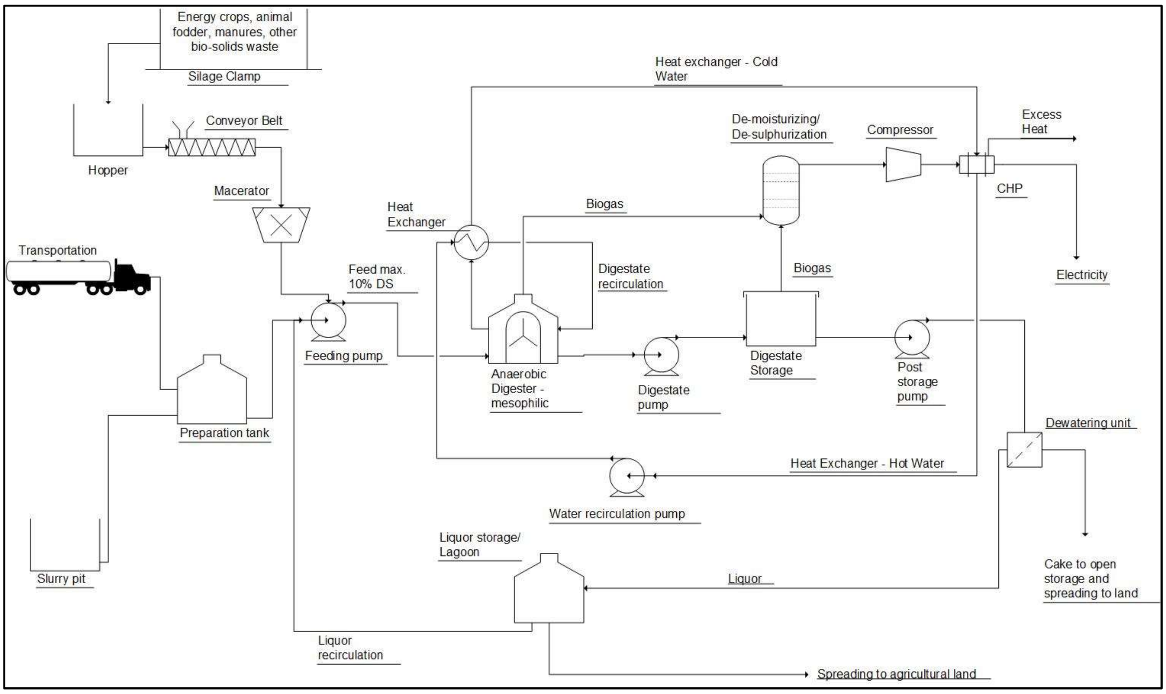


Figure 4-1: Comprehensive flow chart representing the layout of the biogas plant. This flow chart can be greatly simplified for small-scale biogas installations.

4.1. Feedstock supply

The AD biogas plant model received agricultural wastes such as livestock waste, i.e. manures, slurries, energy crops (e.g., from maize and grass silages), crop waste and other residues. Inputs to the model were the total annual wet weights of each feedstock in tons or m^3 per annum. The digestion was assumed to occur under wet mesophilic conditions at a temperature of 38 °C, which is typical of operational sites in the UK.

The ideal dry solid concentration in the main digester should be maintained possibly below the ideal target of 10 %, which is the best compromise between viscosity and ease of pumping and mixing (Wellinger *et al.*, 2013). In fact, fluid viscosity should be controlled within certain bounds to make sure that the influent is pumpable and to minimize the energy needed for mixing.

Dilution of the influent is assumed to be necessary ifdry solid concentration of the feedstock mixture exceeds 14%. Dilution primarily comes from the liquor stream from digestate separation. Rainwater collected from rooftops and floors and any leachate from silage clamps can provide further dilution. Water from mains should be the last resort, if dilution is not sufficient to achieve the target. Dilution was calculated by applying a mass balance to the mixing tank pre-digestion as illustrated in Equation 4-1, neglecting any accumulation and biodegradation of dry solids (Ghanavati, 2018):

$$\mathrm{Q_{in}} \times \mathrm{DS}_{in} + \mathrm{D} \times \mathrm{DS}_{liquor} = (\mathrm{Q_{in}} + \mathrm{D}) \times \mathrm{DS}_{Target}$$

Equation 4-1

Rearranging Equation 4-1, D can be found as:

$$D = Q_{in} \times \frac{(DS_{target} - DS_{in})}{(DS_{liquor} - DS_{target})}$$

Equation 4-2

Where:

- Q_{in} is the total annual wet tonne of feedstock utilized.
- DS_{in} is the dry solids content of thetotal annual wet tonne of feedstock utilized .
- DS_{target} is equal to 10 % or the minimum target dry solids content to achieve in the digester.
- DS_{liquor} is set to 1 %, it is the dry solids content in the dilution stream.

At the commissioning stage, it is common practice to fill the digester up with digestate sourced from nearby biogas plants. The dry solids fed to the digester every day is a small fraction of the entire digester volume. In addition, its bio-degradable fraction is quickly converted into methane in the first few days while dry solids leave the digester in the outlet. As a result, even if the influent dry solids concentration is above 10 % the combined effect of volume dilution and solids removal via biodegradation in the digester might be sufficient to make dilution unnecessary.

Substrates from crop materials such as maize silage, grass silage, straw and other crop residues were loaded into a solids feeding machine, then fed to a macerator before mixing with slurries and dilution streams. This ensured that particle size was small enough (ideally smaller than 12 mm) to prevent blocking in the pipework, tear of mechanical components, floating layers in the digester and improve biodegradation rate. This configuration changed for small-scale systems mostly fed with slurries and waste maize fodder silage where the solids were fed directly into the pre-digestion preparation tank.

The feeding pump at biogas installations was designed to operate between 10 to 20 min every hour. This led to estimate the total number of hours that the pump is on in a year and the average flowrate by dividing total annual wet tonne of feedstock by operating hours of the pump. It was assumed that the feeding pump can empty the digester in 24 hours. This determined the pump capacity and relative Capital Expenditure (Capex).

4.2. Main digester and storage tank

Equation 2-17 was used to describe the kinetic of the digester with the four parameters estimated via the non-linear least square method implemented in MATLAB® with data on *HRT, BMP* and $VS\%_{manure}$ derived from the eight case studies. Dividing Equation 2-14 by BMP_u^{Mix} gives:

$$\frac{BMP}{BMP_o^{Mix}} = \frac{HRT \times k_{Mix}}{HRT \times k_{Mix} + 1}$$

Equation 4-3

Equation 4-3 indicates the extent of which the biodegradation of the organic fraction of the waste in the reactor is close to its full potential. This measure is not the same as the VS destruction realized in the digester that should derive from direct measurements. The ratio between the BMP achieved in the digester and the ultimate BMP of the feedstock mix according to Buswell equation is a more representative measure of the total COD removal efficiency. Nonetheless, the ratio indicated by Equation 4-3 is still a good measure to estimate the minimum HRT required to meet a specific percentage of the full biodegradation potential achievable in the main digester.

The net digester volume required to accommodate total feedstock volume is calculated by multiplying the daily influent flowrate by the HRT. This is then divided by a factor 0.95 to get the total volume of the digester and, subsequently, the total surface area including floor, roof and walls for heat losses calculations.

National legislation in the UK sets rules for minimum storage time requirement for slurries in Nitrogen Vulnerable Zones (NVZs). For instance, these rules dictate that the minimum storage time is 150 days in NVZs rising to 180 days for pig slurry and poultry manure. In the storage tank the anaerobic degradation of the volatile solids continues although at slower rates due to lower temperatures. If the storage tank has thermal insulation then temperature drop is expected to be within 1 °C per week (Personal communication with Michael Köttner of IBBK Fachgruppe Biogas GmbH). Linke *et al.* (2013) investigated how BMP changed with time and temperature in the storage tank finding the following relationship:

$$BMP_{Storage} = (BMP_o^{Mix} - BMP) \times \left(1 - e^{-k^S(T) \times HRT}\right)$$

Equation 4-4

Where k^s (T) is a parameter depending on temperature according, to the Arrhenius equation:

$$k^S(T) = k^S(22°C) \times 1.148^{T-22}$$

Equation 4-5

This was valid for temperatures between 22 °C and 37°C. k^s (T) is 0.0063 at 22 °C and 0.05 at 37 °C. Therefore, total BMP achieved after storage was estimated as follows:

$$BMP_{total} = BMP + BMP_{Stora}$$

Equation 4-6

From the case studies it emerged that it was common practice to store digestate in tanks on site typically from a few days to a few weeks to reduce costs. Digestate was then separated into liquor and cake fractions and, finally, the liquor was pumped into a lagoon for long term storage to meet the required minimum storage time. This scenario was more representative of on-farm AD systems within the UK context.

4.3. Biogas Production and end uses

Methane and biogas production were calculated by multiplying total *BMP* by total *VS* added to the digester and methane losses:

$$APPM_{Plant} = BMP_{Total} \times VS_{total} \times \%Losses\_CH_4$$

Equation 4-7

Methane losses should be kept to a minimum, ideally below 1 %. However, higher methane losses could occur at biogas installations. Finally, the total energy embedded in biogas was:

$$APPE_{Plant} = APPM_{Plant} \times LHV_{CH4}$$

Equation 4-8

Where LHV_{CH4} is the Low Heating Value of methane, and equal to 37.78 MJ m^{-3} (Wellinger *et al.*, 2013). Biogas can be used to produce just heat with boilers, both heat and electricity in cogeneration units, or it can be upgraded to bio-methane for gas grid injection or transportation fuel. Gas to grid applications require expensive equipment. Biogas upgrading can only be financially justifiable for large biogas throughputs, typically higher than 800 m^3 h^{-1} (Personal Communication with Steve Rowntree of Green Lane Technologies).

This throughput would equate to scales of operation that are unlikely to be achievable for agricultural applications, particularly in the UK where most sites are associated with single farms using their own waste. Heat and electricity production in CHP units is by far the most common application at operational biogas plants in the UK due to their flexibility, efficiency and versatility. However, excess heat is often wasted due to lack of eligible end uses in proximity to the engine.

The electrical efficiency and thermal efficiency of a CHP unit depend on the size of the engine but, indicatively, they are of the order of magnitude of 38 % and 45

% (Wellinger *et al.*, 2013). CHP units typically operate between 90 and 95 % efficiency. Electrical output and electricity produced were calculated by the following equations:

$$W_{CHP} = \frac{APPE_{Plant} \times 1000}{365 \times 24 \times 3600} \times \eta_{el}$$

Equation 4-9

Where η_{el} is the electrical efficiency of the CHP unit, which depends on the size of the engine varying between a minimum of 35 % and increasing up to a maximum of 40 % for large engines.

$$E_{kWh} = W_{CHP} \times Op\_hr$$

Equation 4-10

Heat output and heat produced in a year were calculated with a similar approach. During CHP downtime, a back-up boiler was used to produce heat.

4.4. Biogas Plant Energy Demand

The total parasitic load of a biogas plant was defined as total heat and electricity required to meet process energy demand. Heat was needed to keep the digester at constant temperature while electricity was required to power all of the equipment.

4.4.1. Heat demand assessments

Part of the heat produced from the combustion of the biogas in the CHP unit was used to keep the temperature in the digester constant. The heat balance at the digester illustrated in Equation 4-11was instrumental to estimate the maximum heat capacity that the heat exchanger had to deliver (Wellinger *et al.*, 2013), and hence the associated capital expenditure:

$$W_{max} = W_{feed} + W_{losses} = c_p \times \Delta T_1 \times \rho \times Q_{in} + U \times A \times \Delta T_{2,Max}$$

Equation 4-11

Where:

- W_{feed} is the heat needed to raise the influent temperature to the digester temperature.
- ΔT_1 is the difference between the influent temperature prior to the heat exchanger and the digester temperature. The temperature of the influent is equal to the minimum monthly average air temperature for the location.
- ρ is density of the feed stream. The relationship between density and dry solids for cattle slurry is a proxy to estimate the density of the feeding stream. Equation 4-12 is valid for *DS* concentrations lower than 10 % (Christensen *et al.*, 2013):

$$\rho = \frac{(DS + 236)}{0.24}$$

Equation 4-12

- Q_{in} is the flowrate of the feedstock stream.
- Specific heat capacity c_p of the feed stream is 4.2 kJ kg^{-1} $°C^{-1}$, that is the same as the specific heat capacity of sewage sludge 4.2 (Metcalf *et al.*, 2003).
- W_{losses} is the heat needed to compensate heat losses through digester walls, roof and floor. Other minor contributions to heat balance such as heat lost through evaporation and reaction enthalpy energy are neglected.
- $\Delta T_{2,Max}$ is the maximum temperature difference between the temperature in the digester and the outdoor minimum air temperature that can occur at the specific location. The outdoor minimum temperature is the average minimum temperature in Bath according to Met Office data (Met Office, 2018).
- *A* is the total surface area of the digester including roof, walls and floor areas.
- *U* is the heat transfer coefficient of the digester. The heat transfer coefficient differs between roof, floor and walls. In practical terms, the thermal coefficient *U* for the roof could be ignored given that biogas in the head space between the liquid surface and rooftop determines a thick insulating layer (Wellinger *et al.*, 2013). Best practices suggest that digesters should be built to achieve an overall heat transfer coefficient *U*

between 0.3 and 0.4 W °C^{-1} m^{-2} for mesophilic digestion and temperature drop limited to within one degree a week. The accurate calculation of the thermal coefficient has not been undertaken since the argument is that the tanks are built according to the state of the art. Therefore, the heat transfer value is set to 0.35 W °C^{-1} m^{-2}.

Equation 4-11 calculates the heat load required by the reactor, expressed in terms of power, under the worst case scenario of minimum air temperature at the specific location. On the other hand, Equation 4-13 estimates total heat demand required to meet digester heat parasitic load, expressed in terms of energy, as the sum of heat losses and heat required to heat up the feedstock mixture to the digester temperature:

$$q = q_{losses} + q_{feed}$$

Equation 4-13

Since heat losses are dependent on air temperature fluctuations throughout the year, they were calculated on a monthly basis with the following equations:

$$q_{losses} = \sum_{i=1}^{12} U \times A \times \left(T_{Digester} - T_{Air,i}\right) \times Hours\ in\ month_i$$

Equation 4-14

Where:

- U (W °C^{-1} m^{-2}) and A (m^2) are respectively the overall heat transfer coefficient of tank and total area of digester including roof, floor and walls.
- $T_{Digester}$ (°C) is the digester temperature
- $T_{Air,i}$ (°C) is the average air temperature of month *i*
- The last term represents the number of hours in month *i.*

Heat to raise the influent to the digester temperature was calculated as follow:

$$q_{feed} = \sum_{i=1}^{12} Q_i \times \rho \times c_p \times \left(T_{Digester} - T_{Air,i}\right) \times Hours\ in\ month_i$$

Equation 4-15

Where:

- Q_i is the average monthly input flowrate (m^3 h^{-1})
- ρ is sludge density (kg m^{-3})
- c_p is the specific heat capacity of sludge, assumed as 4.2 kJ kg^{-1} C^{-1}

Total heat demand was then compared with the total heat output from the CHP unit to calculate the net thermal energy in kWh_{th} available and the heat parasitic load as the ratio between total heat demand and the heat output from the CHP unit.

4.4.2. Energy for pumping

The estimation of the energy required for pumping stems from the energy balance applied to the pipework (Coulson *et al.*, 2005):

$$\Delta H = Static\ Head + Difference\ in\ sytem\ pressures\ + Pressure\ drops\ in\ pipes$$
$$= (z_1 - z_2) + \frac{(p_1 - p_2)}{\rho \times g} + \frac{\Delta p_{Losses} \times L}{\rho \times g}$$

Equation 4-16

Where:

- ΔH (m) is the total head that the pump has to deliver. If ΔH is negative, a pump is not required.
- z_1 and z_2 (m) are water levels in tank 1 and tank 2.
- p_1 and p_2 (Pa) are pressures in the head space of tank 1 and tank 2.
- Δp_{Losses} (Pa) are energy losses due to friction between tank 1 and tank 2. Energy losses due to fittings and bends are ignored. If the fluid goes through a heat exchanger the additional pressure drop is accounted for.
- L (m) is the pipe length between tank 1 and tank 2.
- ρ (kg m^3) is sludge density
- g (m s^{-2}) is gravity constant, 9.81

Pressure drops in pipes were calculated using the Darcy-Weisback formula (Coulson *et al.*, 2005):

$$\Delta p_{Losses} = 8 \times f \times \frac{1}{d} \times \frac{\rho}{2} \times v^2$$

Equation 4-17

Where:

- *d* (m) is the internal pipe diameter
- *ρ* (kg m^{-3}) is density
- *v* (m s^{-1}) is velocity
- *f* is the friction factor

The friction factor depends on Reynolds number (*Re*) and other factors. *Re* is representative of the type of flow in the pipe:

$$Re = \frac{\rho \times d \times v}{\mu}$$

Equation 4-18

The flow is laminar for *Re* <~ 3000 and turbulent for higher *Re*. Depending on the type of flow, the friction factor was calculated as:

$$f = \frac{64}{Re}\ for\ laminar\ flow$$

Equation 4-19

$$\frac{1}{\sqrt{f}} = -2 \times log_{10}\left(\frac{\frac{\epsilon}{d}}{3.7} + \frac{2.51}{Re \times \sqrt{f}}\right) for\ turbulent\ flow$$

Equation 4-20

Where ε is effective roughness height of pipes. Viscosity of cattle manure depends on *DS* content according to the following equation (Jensen *et al.*, 2013):

$$\mu = 4 \times 10^{-5} \times DS^{4.4661}$$

Equation 4-21

Density and viscosity of cattle slurry were taken as reference for calculation of pressure drops in pipes, since this was the base component in the feedstock mix of most agricultural biogas plants in the area of investigation. It was assumed that the flow in the pipework is laminar.

Table 4-1 shows that laminar flow is a legitimate assumption for cattle manure at 10 % DS content in stainless steel pipes, with an internal diameter of 150 mm and a flow velocity of 0.5 m s^{-1}.

Table 4-1: Calculation of the type of flow in the pipework and energy losses

Variable	Units	Value
Density	kg m^{-3}	1025
Viscosity	Pa s	1.17
Re	-	67
Friction Factor	-	0.95
Pressure drop per unit length of pipe	Pa m^{-1}	6671
Head loss per unit length of pipe	-	0.69

Head losses due to headspace pressure difference between tanks could be assumed as negligible when compared with the other two terms in Equation 4-16. If it is assumed that in the tanks the relative head space pressure is 20 mbar (Personal communication with Jack Crassweller of Wessex Water) and static head between the preparation tank and the digester tank is 10 m, then the head space pressure difference accounts for just about 1 % of the required total head. Equation 4-16 was applied to each pipe section between tanks to estimate total head needed and, subsequently, energy consumption:

$$E_{kWh,pumping} = \frac{Q_{in} \times \rho \times g \times \Delta H}{\eta} \times Operating\ hours$$

Equation 4-22

Where:

- Q_{in} (m^3 h^{-1}) is flowrate of the feeding stream
- ΔH (m) is total head in
- ρ (kg m^{-3}) is sludge density
- g (m s^{-2}) is gravity
- η is pump efficiency set to 0.7

Pumping was also required to recirculate sludge in the digester through the heat exchanger to make up for heat losses. Equation 4-13 determines the average heat load required to meet the heat demand by month. It was straightforward to calculate the mass flowrates of water and sludge required in the heat exchanger to meet the average heat load and, subsequently, the pumping energy requirements in kWh via Equation 4-22.

4.4.3. Energy for dewatering

The dewatering unit separated solids from the liquid fraction and was situated after the digestate storage tank. The liquor was sent to the lagoon while the cake was discharged and stored outdoor. Screw pumps are common applications in agricultural biogas plants while centrifuges are more applicable to bigger plants. A centrifugal pump typically requires power capacity between 1 and 2 kW m^{-3} h^{-1} of flow treated (Personal communication with Keith Oliver of Alpha Laval Ltd). This value was taken as a reference for energy consumption calculations. It was assumed that the machine operating hours were the same as the feeding pump. The machine was capable to achieve 90 % dry solids percent removal and 24 % DS in the cake.

4.4.4. Energy for mixing

Sludge underwent mixing in the digester tank, and less so in the preparation and storage tank, to ensure optimal conditions for biogas production. Mechanical mixing is the most common system installed at biogas installations. Mixing power capacity depends on the dry solids content and viscosity of the sludge, among other parameters. Table 4-2 shows the relationships between power requirements and tank volume under various feedstock mix scenarios according to technical advice from a technology provider (Personal communication with Maja Rosiak of Xylem Water Solutions).

Table 4-2: Equations are representative of the relationships between power capacity of the mixing system and volume of the tank extrapolated from the information provided by the technology supplier (Xylem Water Solutions).

Scenario (DS<10%)	Equation	R^2
Mono digestion of cattle manure	$E_{kWh,mixing} = 0.0014 \times {V_{Tank}}^{1.1645}$ Equation 4-23	0.98
Mono digestion of pig manure/co-fermentation	$E_{kWh,mixing} = 0.0097 \times {V_{Tank}}^{0.9517}$ Equation 4-24	0.98
Co-digestion	$E_{kWh,mixing} = 12.501 \times e^{0.0002 * V_{Tank}}$ Equation 4-25	0.89
Mono digestion of maize	$E_{kWh,mixing} = 13.535 \times e^{0.0003 * V_{Tank}}$ Equation 4-26	0.89
Mono digestion of grass	$E_{kWh,mixing} = 14.163 \times e^{0.0003 * V_{Tank}}$ Equation 4-27	0.89

Figure 4-2 illustrates that with an increasing proportion of crops in the feedstock mix the power capacity required for mixing soars accordingly. This is what is expected since with the addition of crop material makes the mixture thicker and more viscous hence harder to stir it. Data points in Figure 4-2 derived from the information provided by the technology supplier (Personal communication with Maja Rosiak of Xylem Water Solutions) for each mono-digestion and co-digestion scenario. The best fitting curves were calculated in Excel.

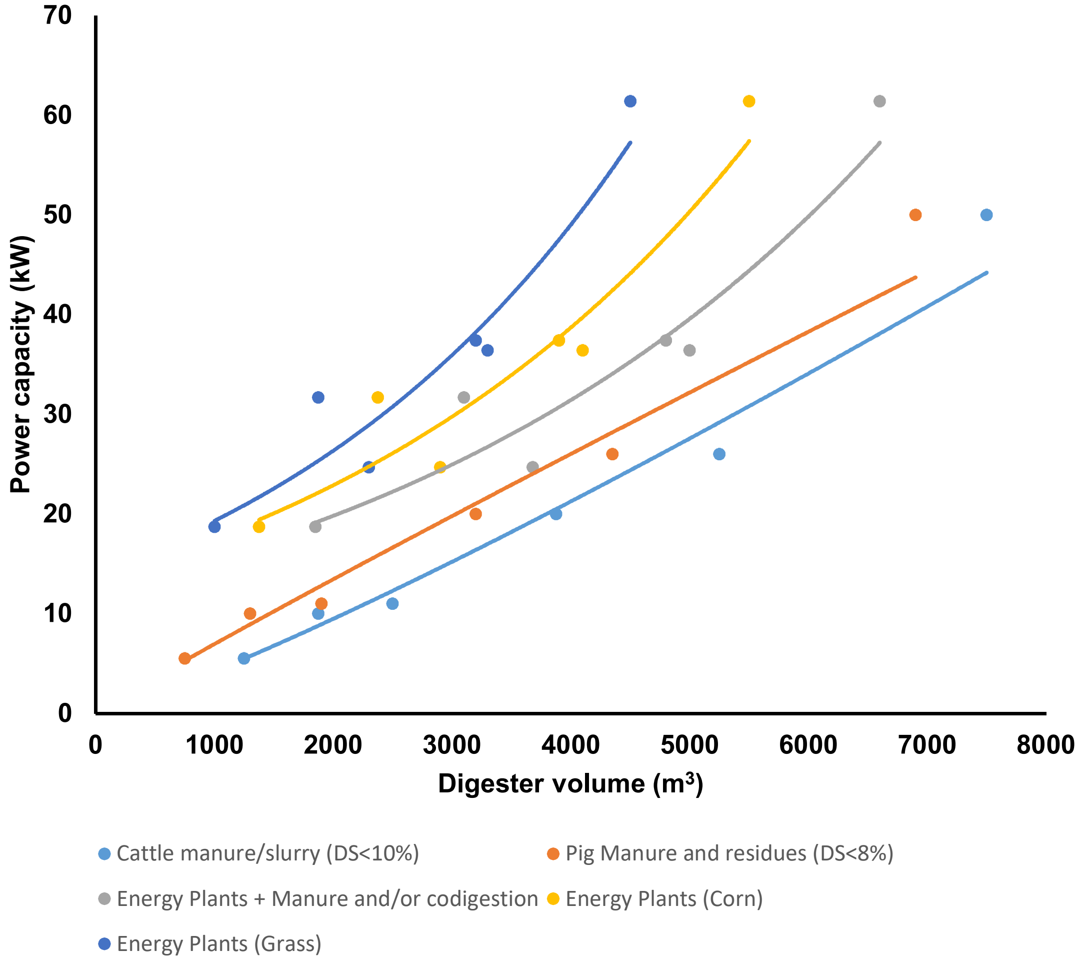


Figure 4-2: Data points and trend lines are indicative of the correlation between digester volume and mixing power capacity needed. Substrates with higher content of fibres are more difficult to stir compared to more diluted substrates such as slurries. Raw data was provided by the technology provider. Equations of trend lines are presented in Table 4-2.

4.4.5. Energy consumption of other main equipment

The macerator cut the solids into small pieces with ideally maximum length of between 10 and 20 mm before mixing with slurry and liquor. This facilitates the breakdown of the organic material and prevents floatation in the digester. The operator loaded the solids feeder daily where solids were mixed together and then fed to the digester either directly via screw conveyors or via a mixing pump. The associated energy consumption for both machines resulted from multiplying the installed drive power by the operating hours. Finally, electricity was needed for lighting, monitoring and control and other auxiliaries. No data were collected or found from the literature attempting a quantification of the energy consumption from these appliances. Equation 4-28 illustrates all terms contributing to the electrical parasitic load of the biogas plant:

$$E_{kWh,parasitic} = (E_{kWh,pumping} + E_{kWh,mixing} + Dewatering + Maceration + Solids\ Feeder)$$

Equation 4-28

4.5. Fertiliser Value Assessment

During anaerobic digestion the total mass of nutrients remains unchanged. However, the mineralisation of nutrients leads to their enhanced availability for plants uptake. Therefore, although the total mass of nutrients do not change in the digester, the fertiliser value of digestate is increased. The positive effect of mineralisation is combined with the nutrient concentration effect. This occurs as a result of the conversion of the organic matter, mostly carbon, into methane and carbon dioxide leading to a reduction in volume.

Organic fertilisers from slurries and manures are recycled back to land anyway independently from anaerobic treatment. This implies that the fertiliser value of organic fertilisers that are fed to the digester was subtracted from total fertiliser value of the whole digestate produced to estimate the net fertiliser value. The fertiliser value of organic fertilisers, i.e. manures and slurries, utilized in the feedstock mix was calculated based on the nutrients available for plant uptake in the form of readily available nitrogen (RAN), phosphates and potash and not of total nutrients content. RAN is the nitrogen that is in the form of ammonium-N, nitrate-N and uric acid-N that are immediately available for plant uptake (DEFRA, 2010).

It was assumed that anaerobic digestion enhances the availability of N in the digestate but did not change the availability of P and K. This led to a conservative estimation of the financial fertiliser value of the whole digestate:

$$FV_{digestate} = TN_{feed} \times RAN_{digestate} \times P_N$$

Equation 4-29

Where:

- TN_{feed} is total nitrogen in the feedstock mix
- $RAN_{digestate}$ is readily available nitrogen in the whole digestate
- P_N is the price of N fertiliser

The net fertiliser value was the difference between the total fertiliser value in the digestate and the fertiliser value in slurries and manures utilised in the feedstock mix:

$$NFV = FV_{digestate} - FV_{manure}$$

Equation 4-30

4.6. Capital Expenditure (Capex) Assessment

Technology suppliers and bioenergy consultants were approached to gather data on budget costs of the main equipment units of the biogas plant. Data was collected through personal communications by phone, emails and interviews. Suppliers were asked to provide high level indicative costs for Capex and Opex. The list of companies thatprovided support, advice and expertise for this study were included in the Appendix B and their contributions were gratefully acknowledged. Budgetary costs were obtained for the following main components of an AD biogas plant:

1. Tanks (Main digester, Storage and Slurry).
2. CHP – combined heat and power.
3. Biogas cleaning-up.
4. Biogas Upgrading.
5. Pumps.
6. Piping.
7. Boiler.
8. Heat exchanger.

9. Flare stack.
10. Mixers.
11. Centrifuge.
12. Silage clamps.
13. Feed pump including macerator & Programming Logic Controller (PLC).
14. Solids feeder and conveyors.
15. Pipework.

The sum of the Capex associated with each item listed above makes the Total Physical Cost (*TPC*) of the plant:

$$TPC = \sum_{i=1}^{n} Capex_i$$

Equation 4-31

The *TPC* was increased by a coefficient to incorporate contingency and minor cost items including (Coulson *et al.*, 2005):

- Site selection.
- Planning.
- Ground Investigation.
- Permitting.
- OFGEM Pre and Full accreditation.
- Commissions.
- Project management.
- Connection to the grid.
- Commissioning and start up.
- Licenses and HSE.

This coefficient varies between 0 and 10 % to account for uncertainties associated with unforeseen costs. It was directly correlated to the complexity of the project. For instance, for small-scale slurry-fed digesters this coefficient could be set to zero whereas for larger plants taking multiple feedstocks and/or waste the same coefficient increases to 10 %.

Table 4-3 summarises the equations used in the model to predict Capex for main equipment. They were extrapolated from the data provided by technology providers on total Capex for each main component of the biogas plant. Tanks for slurries, digestate storage and main digester were built with glass fused to steel panels and glass coated to steel for digester roofs. Digester tank walls were insulated with 75 mm thick rockwool, which was upgraded to achieve the target weekly temperature drop of 1 °C. Contingency factor accounted for extra costs to upgrade thermal insulation.

The heat exchanger was an industrial stainless-steel double tube heat exchanger. The technology provider provided pressure drops and total Capex for various duties or heat loads in kW and sludge/water flowrates.

The feeding pump was composed of a macerator and a mixing pump. The technology provider quoted machines capable of delivering throughputs ranging from 40 m^3 h^{-1} to 100 m^3 h^{-1}. Costs for pipework were representative of commercial stainless steel with internal diameter between 15 and 350 mm (Coulson *et al.*, 2005).

A back up boiler was needed to ensure continuity in the production of heat and was included in the total Capex estimation with a unit cost of £90 per kW_{el} installed based on information gathered from experienced consultants (Personal communication with Ian Forsyth of 2-G Energy Ltd).

Table 4-3: List of equations representative of unit costs for each main equipment. Correlations were directly derived from data on costs provided by technology suppliers mentioned in Appendix B.

Equipment	Equation	R^2
Digester Tank	$Capex = 84.189 \times V_{Tank} + 45{,}108$ Equation 4-32	0.99
Storage Tank	$Capex = 36.831 \times V_{Tank} + 11{,}719$ Equation 4-33	0.99
CHP	$Capex = 380.79 \times W_{CHP} + 87{,}982$ Equation 4-34	0.86
Biogas cleaning-up	$Capex = 7{,}357.4 \times ln(W_{CHP}) - 9{,}978.9$ Equation 4-35	0.97
Heat Exchanger	$Capex = 192.19 \times W_{max} + 2{,}270.6$ Equation 4-36	0.99
Feeding Pump	$Capex = 575 \times P_{capacity} + 892.86$ Equation 4-37	0.93
Mixing	$Capex = \begin{cases} [4.4989 \times V_{Tank} + 1{,}816.7]\ if\ mono-digestion\ of\ cattle\ manure \\ [4.6264 \times V_{Tank} + 4{,}312.4]\ if\ mono-\ digestion\ of\ pig\ manure/residues \\ [7.6636 \times V_{Tank} + 12{,}363]\ if\ co-digestion \\ [8.7359 \times V_{Tank} + 14{,}995]\ if\ mono-digestion\ of\ maize \\ [10.337 \times V_{Tank} + 16{,}467]\ if\ mono-digestion\ of\ grass \end{cases}$ Equation 4-38	0.99 0.99 0.96 0.95 0.96
Centrifuge	$Capex = 25080 \times (Q_{in} + D)^{0.3997}$ Equation 4-39	0.99
Biogas Flare (half covered flare)	$Capex = 3{,}388 \times W_{CHP}{}^{0.3127}$ Equation 4-40	0.97
Silage Clamp	$Capex = 46 \times Ton + 90{,}000$ Equation 4-41	-
Solids feeder and conveyors	$Capex = 7000 + ((1300 \times Capacity) \times 0.9)$ Equation 4-42	-
Pipework	$Capex = 31 \times d^{0.62} \times L$ Equation 4-43	-

4.7. Operational Expenditure Assessment

Routine maintenance and insurance costs were respectively 2 % and 1 % of Total Capex (Redman, 2008) . The retail price of electricity from the national grid and the sale price were set respectively to £0.10 and £0.06 (Ofgem, 2018a) per kWh for modelling purposes.

Hours of labour needed per annum increaseed with the biogas plant size. According to Köttner *et al.* (2008) a minimum of 500 hours of labour per annum was required (e.g., for biomass loading) for agricultural biogas plants, rising linearly with plant size up to 1,500 hours (circa 4 hours per day) for a 500 kW_e installation (Jones *et al.*, 2013). The minimum hours of labour needed was set to 400 at a cost of £20 per hour (Personal communications with biogas plant operators) increasing linearly with plant size up to 1,500 hours a year for a plant with 500 kW_e.

The cost of servicing of the CHP was estimated from information provided by technology suppliers (2 G energy, Gen-C Ltd, Quantum ES Gas Engines) and was reported in Table 4-4. A major overhaul of the CHP unit was required every 8 years.

Table 4-4: Equations referring to servicing of the CHP extrapolated from data provided by technology suppliers (2 G energy, Gen-C Ltd, Quantum ES Gas Engines)

Item	Equation	R^2
Servicing	$Opex = 102.11 \times W_{CHP}^{-0.613}$ Equation 4-44	0.84
Overhaul	$Opex = 1{,}887.4 \times W_{CHP}^{-0.6857}$ Equation 4-45	0.99

Professional advice could be required to optimize biological optimization and stabilisation of the digester. The extent of professional advice for biological optimization and laboratory analysis is very site specific, depending on the feedstock mix used to feed the digester and the complexity of the plant. Most operators of small to medium size biogas plants reported that they limited sampling and laboratory analysis to the bare minimum, approximately once quarterly, since they did not see much benefit in increasing the frequency of sampling. Costs of de-sulphurisation, laboratory analysis, ammonia inhibition and micronutrients addition were extrapolated from information gathered from Adrian Rochefort of FM BioEnergy. These costs were summarised as follows:

- De-sulphurisation ranged from £2 d^{-1} up to £65 d^{-1} for AD plants up to 500 kW_{el} capacity. It is assumed that costs varied linearly between these values and de-sulphurisation was required once every four days.
- Laboratory analysis were required ideally once every fortnight at a cost of £100 per sample. However, this requirement lowered to one sample every month for slurry only fed AD plants at a cost of around £60 per sample.
- Ammonia inhibition was only required in case of poultry manure in the feedstock mixture. Costs ranged from £2 d^{-1} up to £65 d^{-1} for AD plants up to 500 kW_{el} capacity. It was assumed that costs varied linearly between these values and ammonia inhibition was required once every four days.
- Micronutrients were not needed for slurry only fed AD plants. In all the other cases, costs ranged from £0.3 d^{-1} up to £4 d^{-1} for AD plants up to 500 kW_{el} capacity. It was assumed that costs varied linearly between these values and ammonia inhibition was required once every four days.

Under current market conditions, digestate has no financial value hence its disposal comes either at no cost or at the transportation cost incurred by farmers to collect it from site. Farmers or contractors take waste to the AD plant and digestate away from it. Transportation costs depend on the type of hauling used and distance as shown in Table 4-5, Table 4-6 and Table 4-7.

Table 4-5: Transportation costs for hauling with a road tanker from AD to farm, 30 m^3 capacity (Personal communication with Sean Hill, GENeco)

Distance (km)	£ per load	£ per wet tonne or m^3
5 km	£100	£3.33
10km	£120	£4.00
15km	£150	£5.00

Table 4-6: Transportation costs for tractor with trailed tanker, 10 m^3 capacity (Personal communication with Sean Hill, GENeco)

Distance (km)	£ per load	£ per wet tonne or m^3
5 km	£60	£6.00
10km	£75	£7.50
15km	£80	£8.00

Table 4-7: Transportation costs for spreading to land (Personal communication with Sean Hill, GENeco)

Spreading	£ per m^3
Minimum	£1.50
Maximum	£2.00

Since the focus of the study was on small to medium scale on farm AD systems with a radius of influence of 5 km for feedstock supply, transportation costs were ignored under the assumption that farmers or contractors would incur in transportation costs of raw manures anyway even without the AD plant. Sale price of grass silage and maize silage were derived from the John Nix Pocketbook (Redman, 2018).

- Sale value of maize silage £33 per wet tonne
- Sale value of grass silage £37 per wet tonne

It is evident that feedstocks derived from crop silages are quite expensive. It was assumed that small-scale on farm AD plants mostly fed with cattle manure used waste fodder animal silage at no cost to supplement the feedstock mixture. As the scale of the installation increases, the remaining fraction of good quality silage was evaluated at market prices. The potential for energy savings at dairy farms was estimated from industry benchmarks on farm energy consumption. At dairy farms electricity consumed can vary between 200 kWh and 600 kWh per cow per annum (DairyCo., 2009).

4.8. Conclusions

The biogas calculator takes the total wet tonne per annum of each component in the feedstock mix as input and returns Capex, Opex, revenues from electricity, heat and fertiliser savings, heat and electric parasitic loads as main outputs.

The level of detail achieved in terms of costing and designing was unique. For instance, the majority of Excel based tools in the literature only considered average values for Capex, Opex, electric and heat parasitic loads. This tool broke down capital and operational costs into every single main cost item and was capable of costing each one of them. Furthermore, costs stemmed from realistic current market prices provided directly by technology providers.

The estimation of the heat and electric parasitic loads was based on, respectively, the heat balance at the main digester and the total electricity consumption calculated as the sum of the energy required for pumping and to power each piece of equipment.

The predictions of the biogas calculator were compared with operational and financial data gathered from eight case studies representative of agricultural biogas plants in the UK. Wu *et al.* (2016) validated their AD design tool against operational data only related to biogas production from a single case study. The aim in this study was to validate the kinetic model underlying the Excel based tool and financial predictions.

The results from the validation of the biogas calculator are presented in Chapter 6. The biogas calculator, once validated, can assist in the financial analysis of AD of agricultural waste to evaluate the Net Present Value (NPV) of the investment and Levelized cost of energy (LCOE).

5. Agricultural bioresource evaluation in England.

This chapter presents results from the use of the biomass resource management tool described in Chapter 3 to evaluate agricultural bioresource availability in England. The aim was to first estimate the technical biomass potential arising from livestock waste that was potentially available to use for AD in England and then quantified the latent biomass resources stemming from livestock waste by comparing the potential biomass resources and current consumption from operational biogas plants.

The assessment of the technical biomass potential from livestock waste was carried out at the national as well as at the 1 km^2 spatial resolution. This potential was then compared with quantities of livestock waste used at AD sites according to data provided by NNFCC Ltd (2018). This enabled to estimate the latent biomass potential.

Finally, the same tool was used to carry out spatial analysis at the 1 km^2 spatial resolution to investigate the policy scenarios of achieving minimum targets on livestock waste utilization via AD. The aim was to estimate the minimum number of small-scale AD plants and their capacities and locations in the region of interest.

5.1. Quantification of the biomass potential from livestock waste

Table 5-1 shows that in England there were approximately 29 million tonnes of manures and slurries in 2016 that could be potentially used to feed AD systems. This quantity refers to the technical potential as defined in the abstract. Percent variation in Equation 5-1 indicates the percent change between 2010 and 2016:

$$Percent\ variation\ [\%] = \left(\frac{Manure_{i,2016} - Manure_{i,2010}}{Manure_{i,2010}}\right) \times 100$$

Equation 5-1

Table 5-1: Methane and energy potentials arising from manures and slurries for AD systems in England in 2016. Estimate of biomass resource potential arising from straw in 2010 is not available.

Manure type	Refer to Equation 3-1. Data from 2010 (wet tonnes)	Refer to Equation 3-1. Data from 2016 (wet tonnes)	Percent variation (%)	APPM Refer to Equation 3-4. Data from 2016 (m^3 CH_4)	APPE. Refer to Equation 3-5. Data from 2016 (GJ)
Cattle Slurry	10,223,547	9,868,370	-3.47	128,604,598	4,858,682
Cattle FYM	13,595,518	12,954,597	-4.71	568,577,262	21,480,849
Pig Slurry	1,472,846	1,566,772	6.38	22,742,009	859,193
Pig FYM	1,852,167	2,025,405	9.35	131,205,736	4,956,953
Sheep FYM	756,759	821,547	8.56	23,880,317	902,198
Layer Manure	789,981	666,311	-15.65	36,940,282	1,395,604
Litter Manure	608,115	660,827	8.67	81,321,371	3,072,321
Horse FYM	478,482	394,731	-17.50	13,766,244	520,089
Goats FYM	4,971	5,209	4.79	281,350	10,629
Total	29,782,386	28,963,769	-2.75	1,007,319,169	38,056,518

Since 2010 the total technical potential, including all types of manure, has declined by 3 % to approximately 29 million tonnes per year. Given the short time span considered, it can be argued that this change could be linked to fluctuations in the total livestock population across all livestock groups from one year to the next. The most noticeable changes have been found for horse farmyard manure with a drop of 17.50 %, and layer manure with a decrease of around 15.65 %. Pig slurry and pig FYM production have increased respectively by 6.38 and 9.35 %, whereas cattle slurry and cattle FYM production have reduced by 3.47 and 4.71 % respectively.

If the entire annual manure production potentially available for AD in England in 2016 was used to generate biogas, this would account for less than 0.6 % of the overall final energy consumption in England. As a result, this source of renewable energy is small in terms of the relative contribution to total energy production at national scale when compared to other energy sources. However, this estimate did not take into account other types of organic wastes that could undergo treatment via anaerobic digestion for energy production. If these types of wastes had been taken into account, their contribution to the overall final energy consumption in England would have been significant.

Straw produced in 2016 was estimated to be around 9,830,627 tons in 2016 in England, which was close to the estimate by Defra of 10,400,000 tons in 2015, of which about 73% was used for animal bedding. As a result, total straw available for other uses amounted to approximately 1,923,144 tons, which was equivalent to 20% of total straw produced. This would add approximately 12,377 GJ of renewable energy production from straw. Tonnes of straw potentially available for AD varied considerably from County to County. In some Counties straw availability could be negative meaning that straw had to be imported to meet local demand. In England this occurred in the West Counties, which imported straw from Counties in the East whose stock of straw exceeds local demand. Straw is bulky and difficult to transport. Therefore, the use of straw as co-substrate in AD could face challenges in the South West.

5.2. Livestock waste utilization at biogas installations

In 2017 approximately 9,793,621 tpa of feedstock were required by biogas plants in England. The average national feedstock mix to existing operational AD systems comprised 16 % manures and slurries, 31 % crops, 34 % food waste, 5 % crop waste and 15 % other waste (NNFCC, 2018). Defra datasets indicated that 2,112,080 tpa of maize were harvested in 2016 for AD in England representing approximately 72 % of 2,925,347 tonnes of energy crops used in biogas plants in England in the same year.

In 2017, almost half of the 382 operational biogas plants in England received manures and / or slurries. Figure 5-1 shows the actual utilisation of livestock waste in England at the end of 2017 calculated as the ratio between current consumption of manures and slurries at operational biogas plants and the estimated biomass potential at county level. This ratio was about 5 % of the available biomass potential, at the end of 2017, confirming that manures and slurries were underutilised substrates for anaerobic digestion in England. It could therefore be argued that there was still considerable potential to develop on-farm anaerobic digestion systems with the right policies in place. The same ratio was below 5 % for most counties rising to almost 10 % in some counties, especially in East counties in England, where most of maize as energy crop was grown.

The area used for producing maize as AD feedstock was between 51,142 and 52,802 ha, which was equivalent to about 1.3 % of total arable land available nationally. About 28 % of land area producing maize for AD in England was located within just two counties in East Anglia and East midlands. While the majority of land used for maize production was located in the South West and East of England, most land specifically growing maize as AD feedstock was concentrated in the East. It emergeed that where the production of maize as AD feedstock crop was significant the uptake of livestock waste was enhanced.

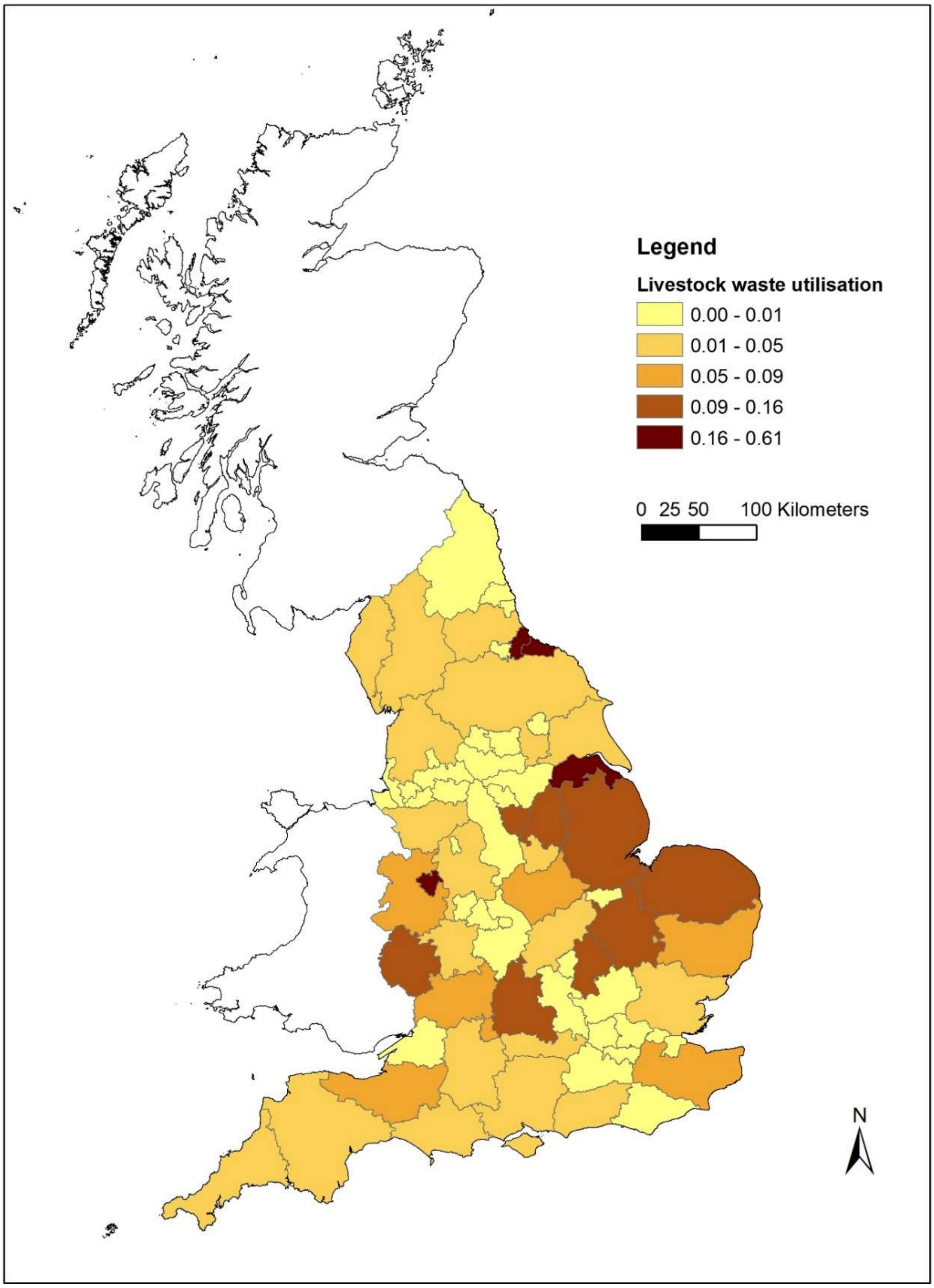


Figure 5-1: Livestock waste utilization by county as the ratio between current consumption of manures and slurries in biogas plants and technical biomass potential from manures and slurries in England in 2016. Darker colours indicate higher livestock waste utilization.

5.3. Biomass potential in the area of study

Table 5-2 shows the technical biomass potential arising from livestock waste in the area that was the focus of this study. Circa 3,889,489 wet tonne y^{-1} of biomass were available to use for biogas production via anaerobic digestion. The region comprised 32 agricultural biogas plants treating approximately 160,650 wet tonne y^{-1} of manures and slurries, which was roughly 4.1 % of the total technical biomass potential.

Table 5-2: Methane and energy potentials arising from manures and slurries for AD systems in the region investigated in 2016.

Manure type	Available manures in 2016 (wet tonnes)	Share by type of livestock waste (%)
Cattle Slurry	1,675,111	43.07
Cattle FYM	1,827,966	47.00
Pig Slurry	84,167	2.16
Pig FYM	109,814	2.82
Sheep FYM	55,009	1.41
Layer Manure	48,332	1.24
Litter Manure	44,467	1.14
Horse FYM	44,623	1.15
Goats FYM	0	0.00
Total	3,889,489	100.00

About 90 % of the total technical biomass potential available for AD stems from cattle slurry and manure. The remaining share was made of roughly 5 % from pig slurry and manure, 2.4 % from poultry manure. If it is assumed that each new biogas plant in the region utilized a feedstock mixture with these characteristics, this would render an average DS content of approximately 18 % yielding approximately 31 m^3 of methane per wet tonne. The DS average content and methane production from the feedstock mixture in Table 5-2 were calculated by applying typical values of DS and BMP_0 from Table 3-2.

In practice, some waste animal fodder silage would be added to the feedstock mixture to improve the biogas yield, typically adding circa 1 tonne per cow per year (Personal communication with Roddy Stanning of RZ Energy Ltd).

Nonetheless, this was still considered the base case scenario of mono-digestion of livestock waste. Figure 5-2, Figure 5-3 and Figure 5-4 show density maps concerning the technical biomass potential at 1 km^2 resolution in the region under investigation from respectively cattle slurry, pig slurry and total poultry manure, which includes both litter and layer manures.

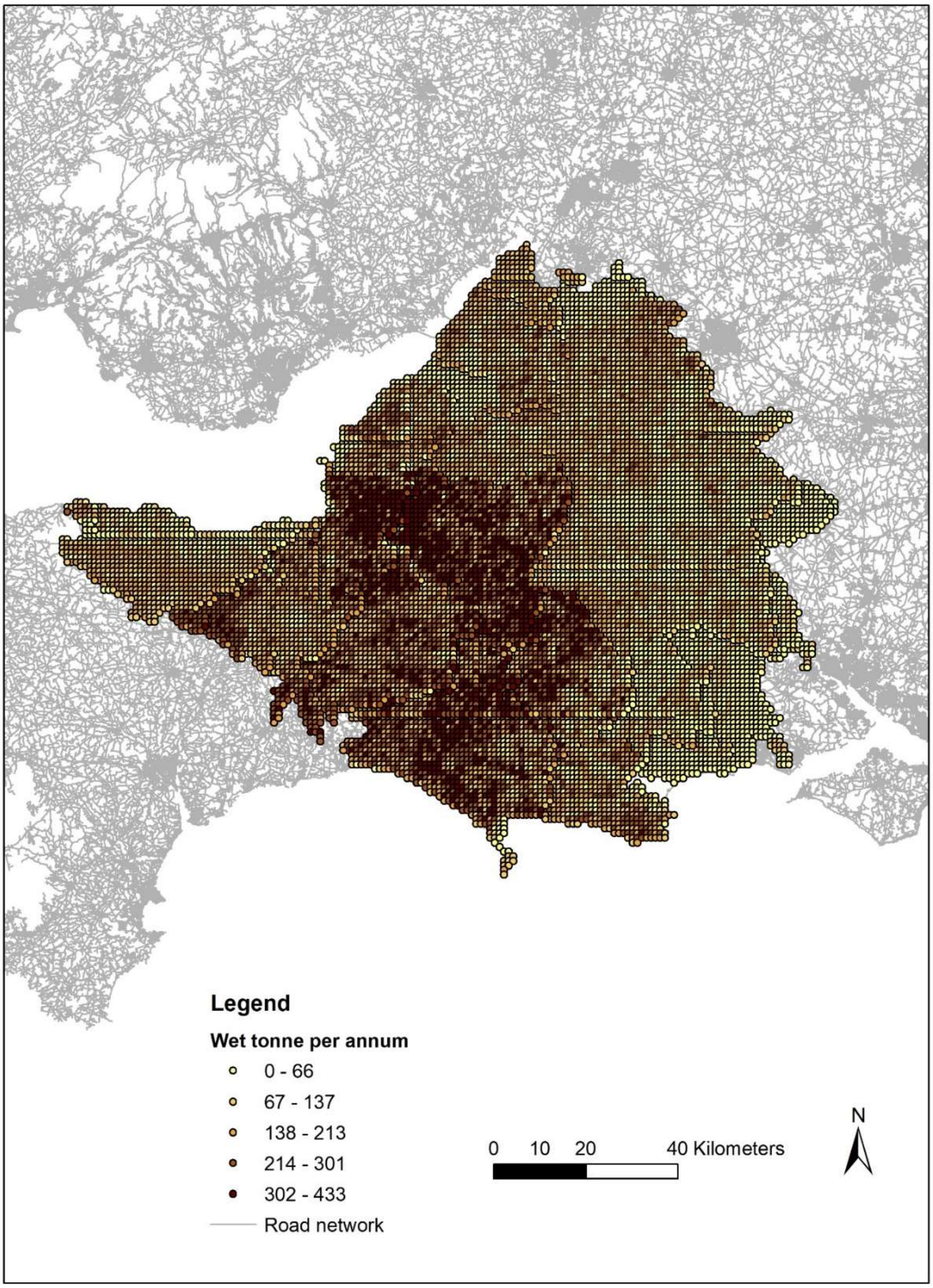


Figure 5-2: Density map at 1 km^2 spatial resolution showing the technical biomass potential arising from cattle slurry in the region.

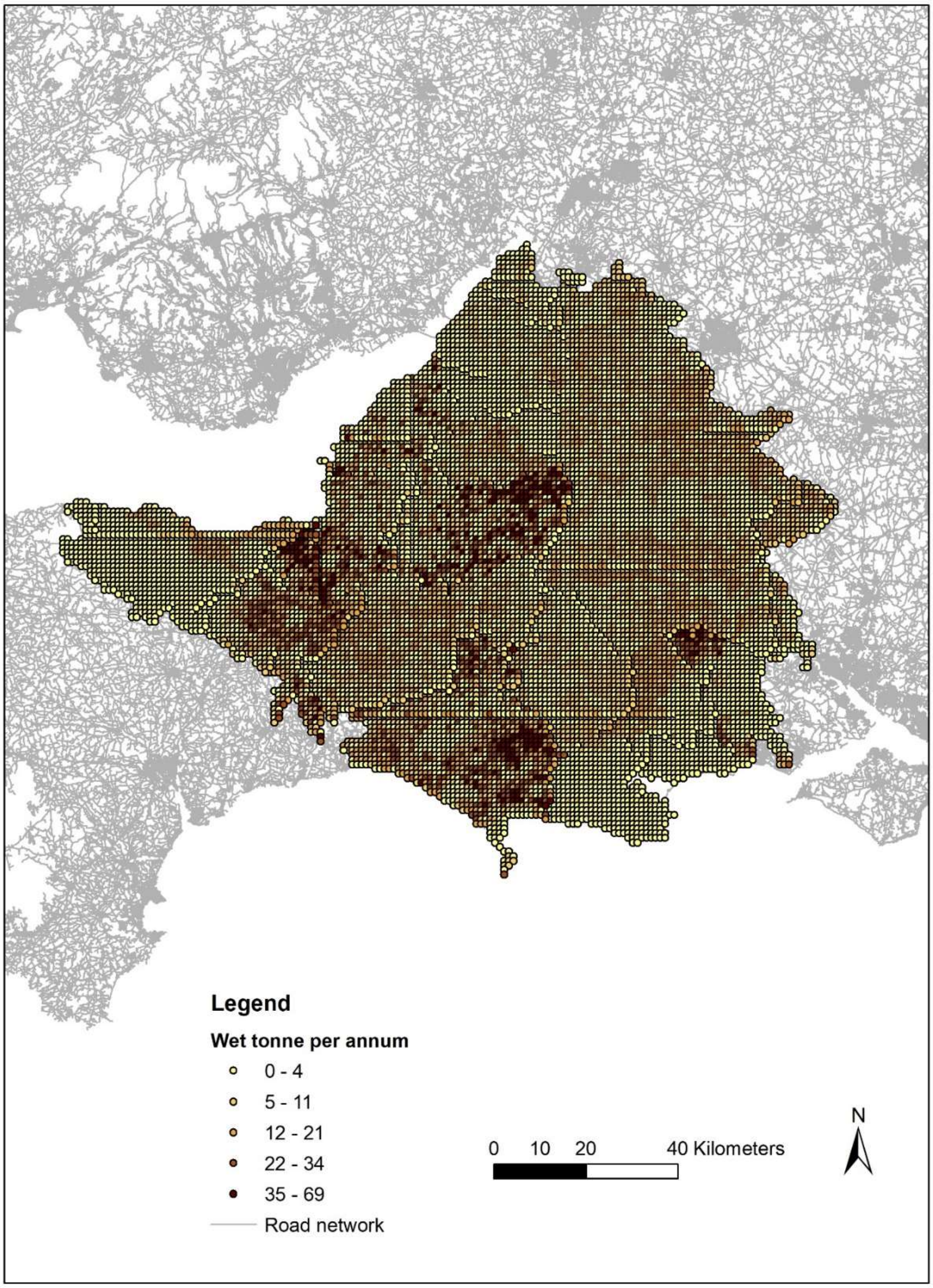


Figure 5-3: Density map at 1 km^2 spatial resolution showing the technical biomass potential arising from pig slurry in the region.

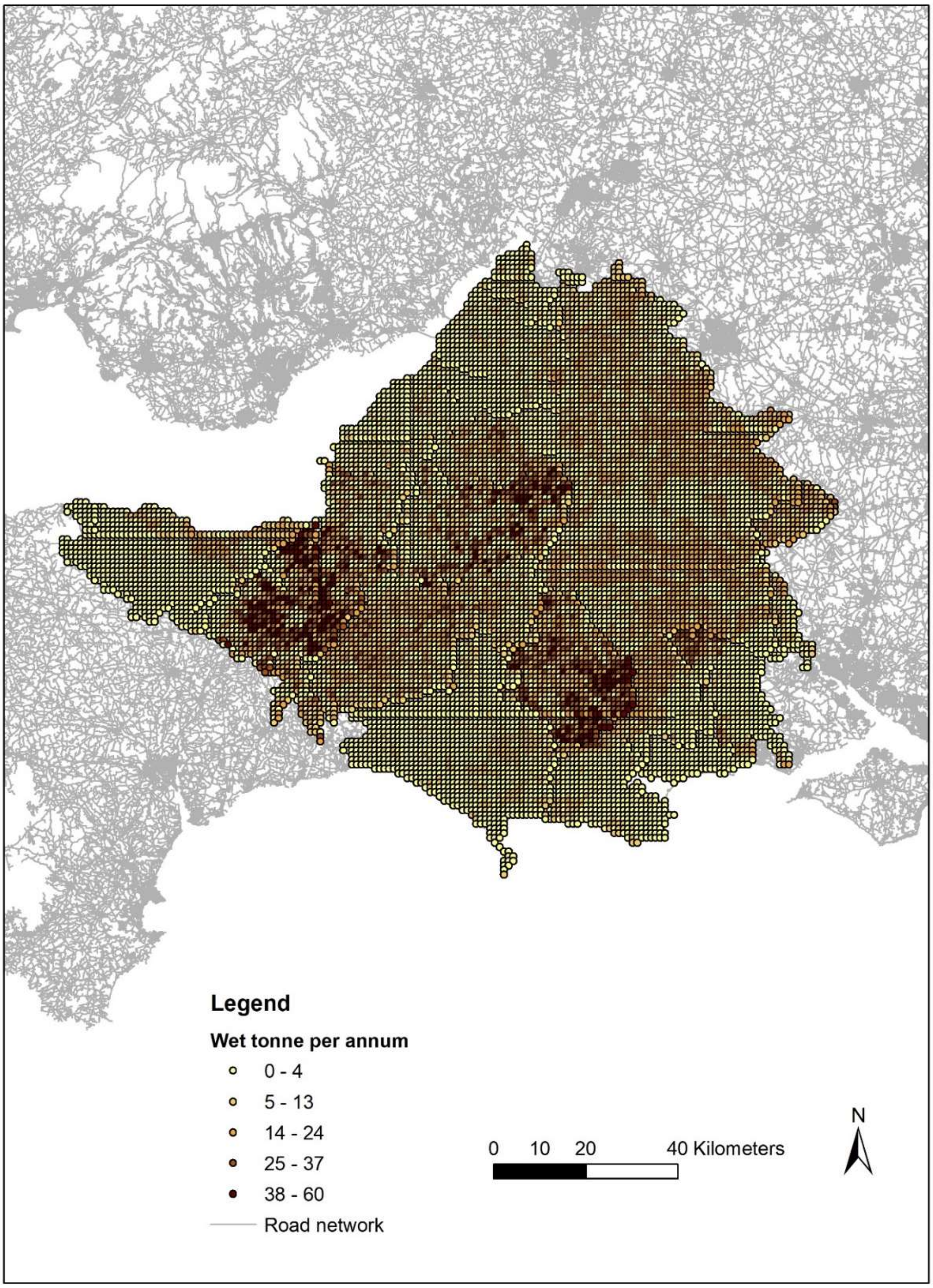


Figure 5-4: Density map at 1 km^2 spatial resolution showing the technical biomass potential arising from poultry manure in the region.

5.4. Implications of meeting policy targets on livestock waste utilization in AD plants

The implications of possible scenarios resulting from environmental policies setting targets of minimum share of manures and slurries to utilize in AD plants were investigated. Two scenarios of environmental policies were evaluated, setting out to achieve minimum targets of 25 % and 50 % utilization of the total technical biomass potential derived from livestock waste. The aim was to find the minimum number of new AD facilities required to meet the target demand share of manures and slurries.

Figure 5-5 shows the map of the chosen locations for new biogas installations to achieve a target share of total manures and slurries utilized in AD plants of 25 %. Service areas including all demand points associated with each facility within 5 km are also shown in brown colour in the map. This would require the construction of 40 new plants with 5 km radius of influence and total capacity ranging between 15,000 and 26,000 wet tonne per annum as in Figure 5-8.

If it is assumed that the electrical efficiency and thermal efficiency of the CHP unit are respectively 38 % and 45 % with circa 8,000 operating hours, this is equivalent to deploy new small-scale AD plants with power outputs spanning from about 122 to 198 kW_{el}. An average pro-capita heat consumption of approximately 13.5 kWh per person per day was estimated, based on total number of households and medium domestic gas consumption in England in 2017 (Ofgem, 2018b). Therefore, the deployment of 40 new plants in the area would generate enough heat to meet the demand for domestic heating and hot water equivalent to 11,955 people.

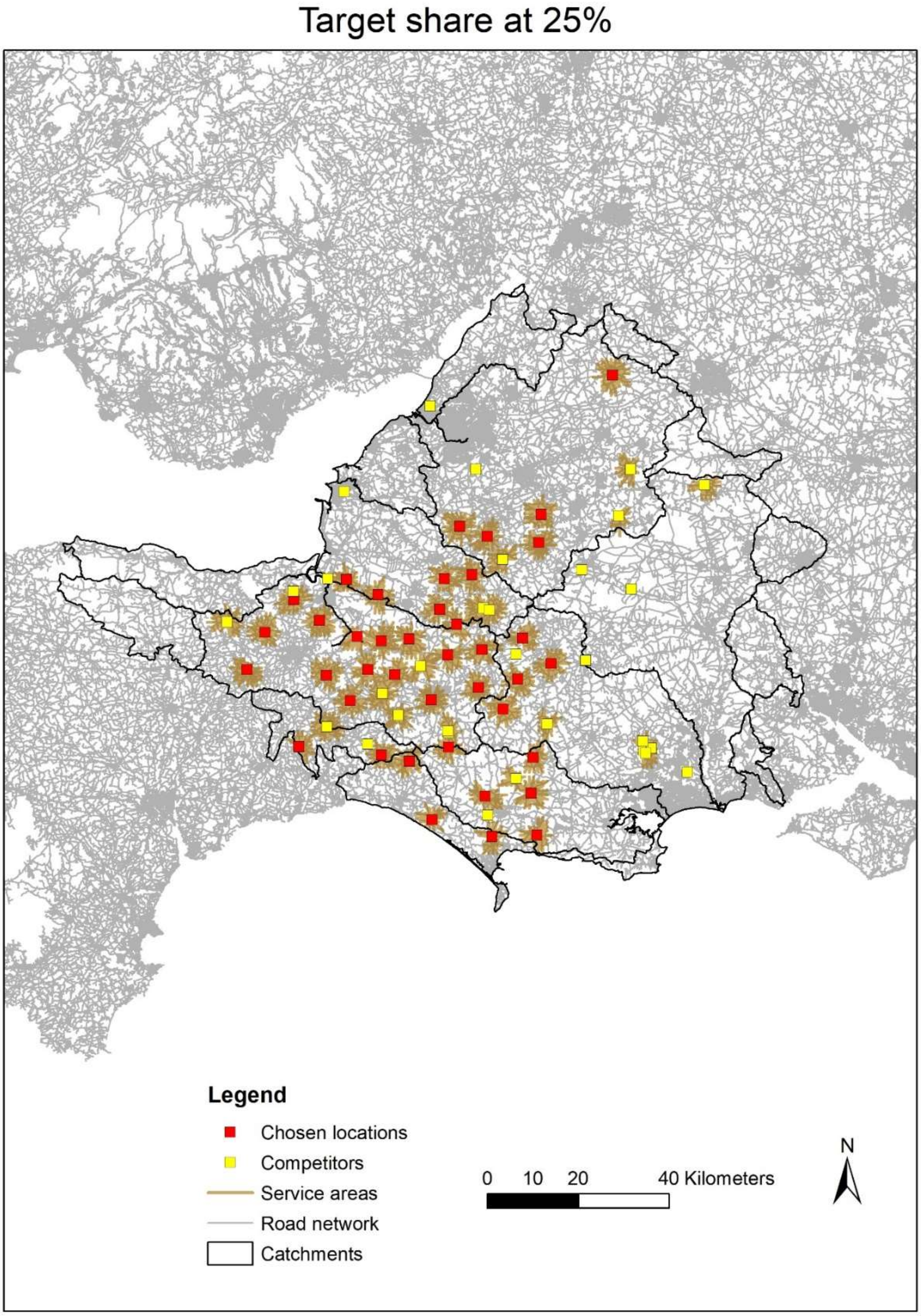


Figure 5-5: Locations of new small-scale biogas installations with associated service areas to achieve 25 % minimum target share of technical biomass potential from livestock waste.

Figure 5-6 shows the map of the chosen locations for new biogas installations to achieve a target share of total manures and slurries utilized in AD plants of 50 %. This would require the construction of 131 new plants with 5 km radius of influence and total capacity ranging between 8,000 and 25,000 wet tonne per annum as illustrated by Figure 5-7. This translated into new small-scale installations with electrical power outputs spanning from about 60 to 190 kW_{el}. This was equivalent to the demand from domestic heating and hot water of 26,752 people. The wider range of capacities found in this case was due to the stronger competition for the same resources between plants.

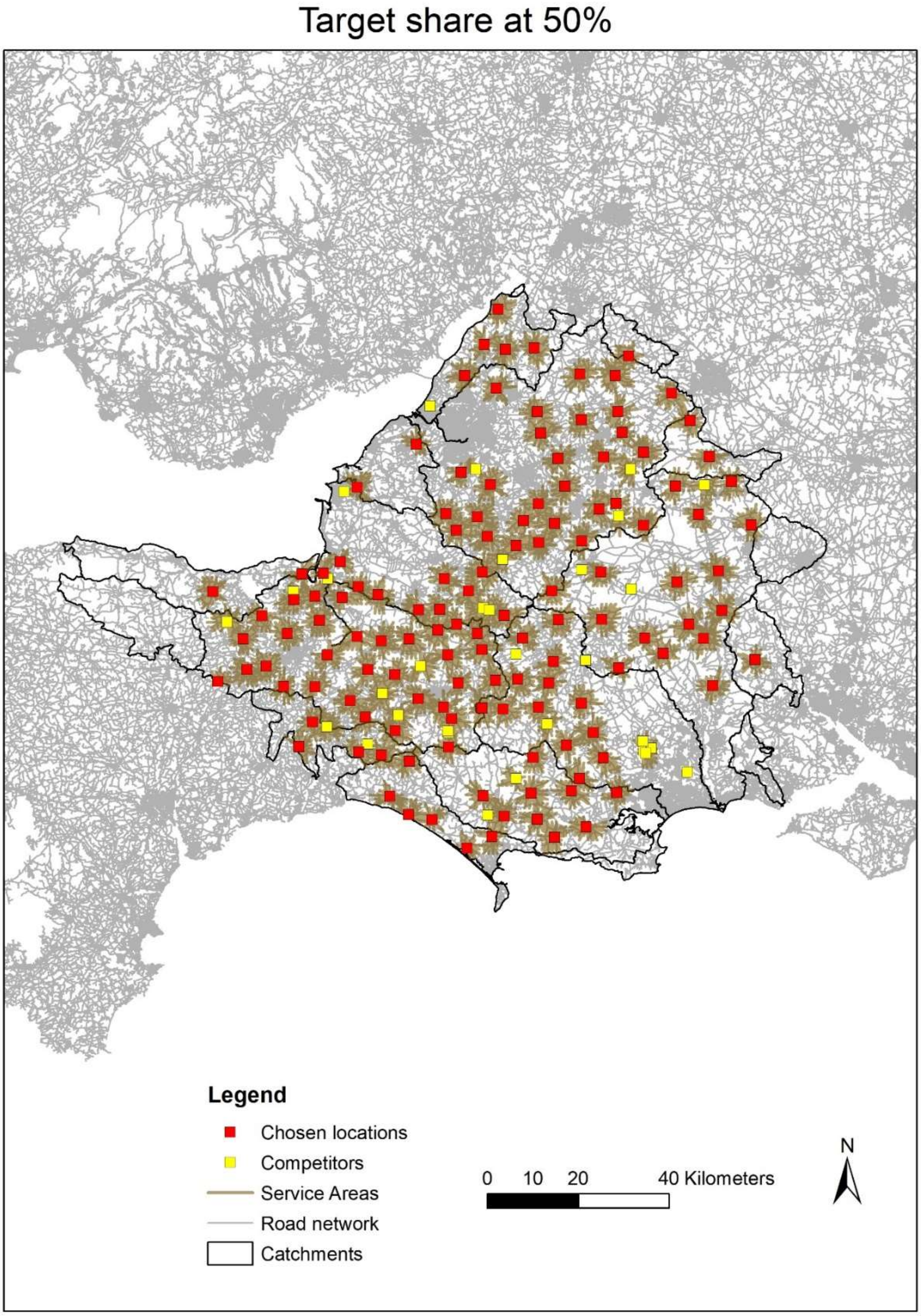


Figure 5-6: Locations of new small-scale biogas installations with associated service areas to achieve 50% minimum target share of technical biomass potential from livestock waste.

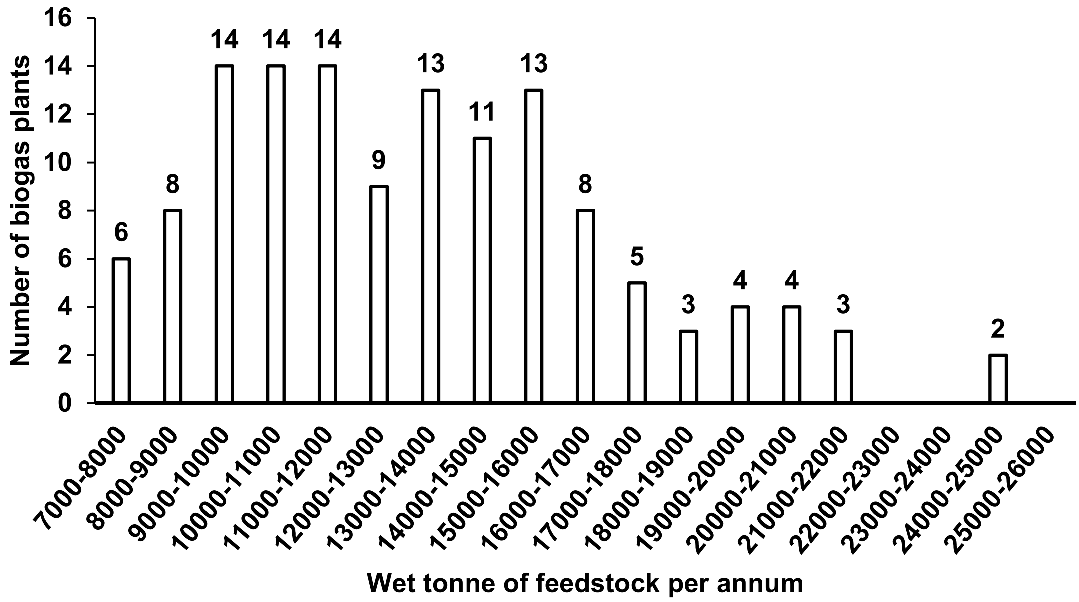


Figure 5-7: Extent of deployment and capacities of new facilities under the hypothetical policy scenario to achieve a minimum target of 50% livestock waste utilized via AD. The numbers above each bar indicates the frequency occurring within each interval.

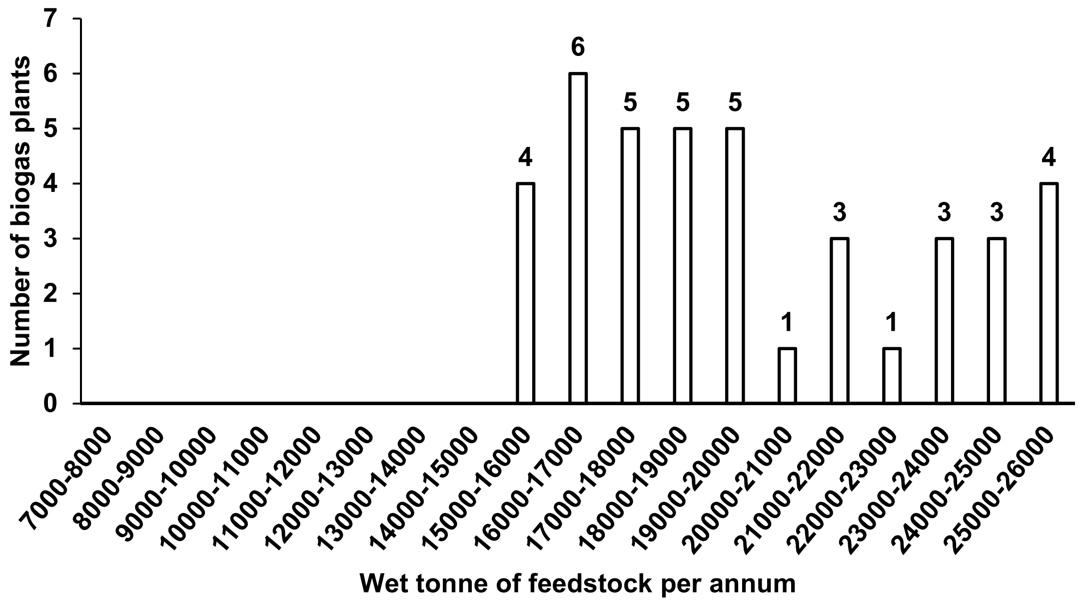


Figure 5-8: Extent of deployment and capacities of new facilities under the hypothetical policy scenario to achieve a minimum target of 25% livestock waste utilized via AD. The numbers above each bar indicates the frequency occurring within each interval.

5.5. Conclusions

The focus of this analysis was on the evaluation of spatial patterns in the biomass potentials at the national and regional scale and scale of opportunities for further on farm AD deployment. This biomass resource potential was compared to the biomass already utilized at biogas installations. This methodological approach could be easily applicable to other areas or regions of the world where data on livestock population structure and size and biogas plants were available.

These findings showed that there were almost 29 million wet tonne per annum of various types of manures and slurries that were immediately available to utilize in AD systems. In England by the end of 2017 the fraction of the total biomass potential utilized via AD to produce biogas was approximately 5 % of the total biomass potential. This figure varied between 0 and 10 % regionally. From the mapping exercise it resulted that the uptake of manures and slurries was enhanced in areas where most energy crops were cultivated. Therefore, these findings showed that there was still a considerable biomass potential stemming from livestock waste in England that could be utilized to produce biogas.

Livestock waste has been almost exclusively utilized at on farm AD plants via mono or co-digestion with energy crops and other farm waste, such as crop waste. There are two ways to enhance the uptake of livestock waste via AD. Firstly, waste management policies and regulations should allow the possibility of mixing livestock waste with other waste streams such as food waste and sewage sludge. Secondly, the cost effectiveness of small scale AD systems based on mono-digestion of animal manures should improve to make them attractive to farmers.

Furthermore, spatial analysis was applied to optimally locate new AD facilities in the region of the South West of England. The aim was to determine the extent of deployment of new facilities needed to meet hypothetical minimum policy targets on the utilization of available livestock waste via AD. This modelling exercise helped to put the previous analysis on biomass resource potential quantification into context in order to evaluate the implications of boosting the uptake of waste from animal husbandry in AD systems.

Approximately 40 new biogas plants mostly fed with manures and slurries with capacities ranging between 15,000 and 26,000 wet tonne per annum were needed to meet a 25 % policy target on minimum biomass utilization. This degree of deployment increased to 131 new plants with capacities ranging between 7,000 and 25,000 wet tonne per annum to meet a 50 % policy target on minimum biomass utilization.

The policy scenarios investigated here were hypothetical in the UK context. However, these policies were already in place in some northern European countries such as The Netherlands, Denmark, Germany and Norway. Therefore it was legitimate to envision such a policy scenario being implemented in the UK soon.

Some changes in environmental policies and financial support schemes to farmers in the UK are already taking place or anticipate possible changes towards this direction. For instance, the strategy set out in the document (Defra, 2018b) states that the covering of slurry storage tanks to abate ammonia emissions from agriculture will become mandatory in 2027. Moreover, subsidies to farmers will be based on the extent of measures taken to reduce their carbon footprint.

6. Evaluation of the kinetic and financial AD plant design model

This chapter firstly provides the highlights from the analysis of the data collected from the eight case studies and lessons learnt from the interviews with biogas plant managers and operators. Data was collected by a paper based survey of the AD process operators during the site visits. A copy of the form used for data collection is presented in the Appendix A.1. The participants were asked to provide data and information concerning:

- Feedstock mix and pre-treatments
- Operational data of the main digester
- Digestate storage and post-treatments
- Digestate management and benefits from digestate spreading
- Biogas production and end uses
- Heat usage
- Capex and Opex

This chapter continues to estimate the four parameters of the kinetic model illustrated by Equation 2-17 via the non-linear fitting curve in Matlab applied to data points from case studies and evaluate the efficiency of agricultural biogas plants measured in terms of VS degradation.

Finally, the predictive capacity of the biogas production calculator was tested against financial data gathered from the case studies in relation to: Capex and Opex, mineral fertiliser savings, heat parasitic load (*HPL*) and electric parasitic load (*EPL*). The description and presentation of the case studies with the associated primary data are presented in Appendix A.

6.1. Feedstock mixes utilized at the AD site

Tables from Table 6-1 to Table 6-8 illustrate the composition of the feedstock mixtures utilized at the AD plants examined in the case studies. Calculations were based on the waste characterization presented in Table A-3 in Appendix A.12. The focus was on agricultural biogas plants using cattle slurry and manure as the base component in the feedstock mixture. The remaining fraction was composed of waste silage, energy crops and other waste from cheese production or vegetable waste. For each Case Study, the share of volatile solids stemming from crops and other waste in the feedstock mix was calculated.

Table 6-1: Feedstock mixture of Case Study 1 and calculations of the share of volatile solids by feedstock type.

Case Study 1: Kemble Farms	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	24000	1176	54.93
Maize (Silage)	1800	605	28.26
Glycerol	182	145	6.76
Maize (Silage)	640	215	10.05
Totals	26622	2140	100.00

Table 6-2: Feedstock mixture of Case Study 2 and calculations of the share of volatile solids by feedstock type.

Case Study 2: Keen’s Cheddar Farm	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	10000	490	88.13
Cheese Whey	1125	66	11.87
Totals	11125	556	100.00

Table 6-3: Feedstock mixture of Case Study 3 and calculations of the share of volatile solids by feedstock type.

Case Study 3: Y farms, Downhead	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	13505	661	64.26
Maize (Silage)	1095	368	35.74
Totals	14600	1029	100.00

Table 6-4: Feedstock mixture of Case Study 4 and calculations of the share of volatile solids by feedstock type.

Case Study 4: Wyke Farms	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	58084	2845	15.21
Cheese Whey	17674	2962	15.84
Straw	1224	1063	5.69
Delactose whey concentrate	7398	3286	17.57
Effluent sludge (from WW)	5618	76	0.41
Maize (Silage)	3661	1230	6.58
Apple pomace	3105	612	3.27
Process bread	7029	6082	32.53
Winter wheat (Silage)	136	44	0.23
Annual ryegrass (Grass) (Silage)	787	242	1.30
Cheese Whey	80	5	0.03
Cattle Manure	175	39	0.21
Factory waste (raw ww)	418	21	0.11
Pig Slurry	9485	192	1.03
Totals	114874	18698	100.00

Table 6-5: Feedstock mixture of Case Study 5 and calculations of the share of volatile solids by feedstock type.

Case Study 5: Bromhouse	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Forage rye (Silage)	10000	3466	25.58
Maize (Silage)	30000	10080	74.42
Totals	40000	13546	100.00

Table 6-6: Feedstock mixture of Case Study 6 and calculations of the share of volatile solids by feedstock type.

Case Study 6: Stowell house	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	20075	983	28.42
Forage rye (Silage)	2190	759	21.94
Maize (Silage)	5110	1717	49.63
Totals	27375	3459	100.00

Table 6-7: Feedstock mixture of Case Study 7 and calculations of the share of volatile solids by feedstock type.

Case Study 7: Hunt family farm	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	3650	179	2.17
Cattle Manure	3650	809	9.81
Layer Manure (Poultry)	10220	3404	41.27
Waste onions	3650	792	9.59
Maize (Silage)	9125	3066	37.16
Totals	30295	8250	100.00

Table 6-8: Feedstock mixture of Case Study 8 and calculations of the share of volatile solids by feedstock type.

Case Study 8: Rushywood farm	Wet tonne per annum	Total VS (tonne per annum)	VS (%)
Cattle Slurry	47450	2324	32.70
Cattle Manure	18250	4047	56.95
Maize (Silage)	2190	736	10.35
Totals	67890	7107	100.00

6.2. Observations drawn from the case studies

Seven AD plants out of eight utilized cattle slurry or cattle FYM in the feedstock mixture. This demonstrates that the majority of the agricultural AD plants in the South West of England used cattle manure as the base component in the mixture thanks to its abundance and widespread availability in the region. There was only one plant referring to Case Study 5 that was fed only with energy crops despite the presence of two dairy units on the same farm.

The small to medium-scale AD plants in Case Studies 1-3, 6 and 8 with electrical outputs between 45 kW_{el} to 500 kW_{el} were located next to the dairy cow sheds. They were mostly fed with cattle slurry, waste silage and other waste streams from cheese or biodiesel production. The smallest AD plants of case studies 2 and 3 utilized only wastes from the dairy farm, respectively cheese whey and waste fodder silage.

A dairy unit typically wastes around 5 % of the silage for animal fodder which is equivalent to roughly 1 tonne of waste silage per cow per annum (Personal communication with biogas plant operator, Case Study 3). This waste can be used in the digester at no cost. However, as the scale of the AD plant increases, the proportion of good quality maize in the feedstock mix rises at the production cost of circa £35 per wet tonne. This was evident in Case Studies 1 and 4 where good quality maize was fed to the digester to boost the yield.

At large biogas installations, they used a wide range of feedstocks such as manures, energy crops, residues from cheese making factories and milk processing, vegetable waste and bakery waste. Biogas was upgraded to gas to grid in Case Studies 4 and 5 where the hourly biogas throughput was higher than 900 $m^3 h^{-1}$. This is deemed to be a cut-off value that determines the commercial viability of biogas upgrading (Personal communication with Steve Rowntree of Green Lane Technologies). Large scale operations had a different order of magnitude of Capex, Opex and energy requirements compared to plants with only cogeneration of heat and electricity.

6.2.1. The economics of biogas production

Figure 6-2 Data on thetotal initial capital expenditure required to build the AD plants presented here were reported by the biogas plant managers. Only available data relative to AD plants using biogas in a CHP unit was used. Biogas upgrading would require an initial investment of a different order of magnitude that did not allow a direct comparison.

Data points representative of Capex versus tank volumes for biogas plants with a CHP unit were best fitted with a trend line shown in Figure 6-1 and described by the equation of a line as follows:

$$\text{Capex} = 1{,}161 \times \text{V}_{tank} - 320{,}158$$

Equation 6-1

$$\text{R}^2 = 0.954$$

Where V_{tank} is the volume of the main digester in m^3.

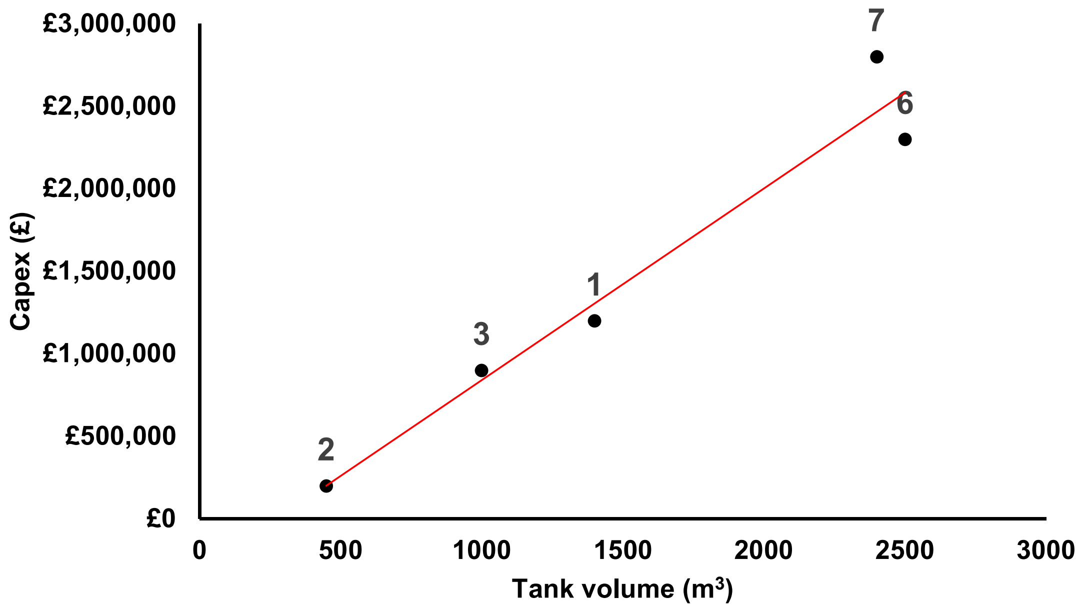


Figure 6-1: The correlation between total Capex and tank volume is fitted well with a linear trendline for biogas plants with CHP units.

Data points representative of Capex versus biogas throughput for biogas plants with a CHP unit were also fitted with a trend line described by the logarithmic equation as follows:

$$Capex = 864{,}154 \times ln(BHT) - 2.680 \times 10^6$$

Equation 6-2

$$R^2 = 0.9528$$

Where *BHT* is the average biogas hourly throughput in m^3 h^{-1}.

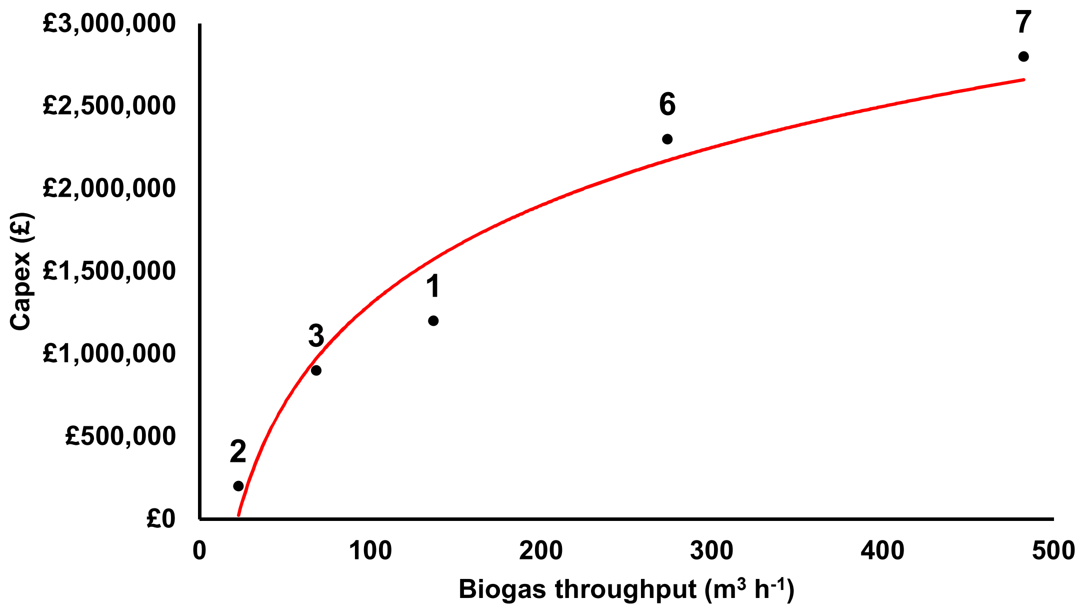


Figure 6-2: Capital expenditure of agricultural biogas plants from the case studies as a function of biogas throughput; black dots represent data points whereas red line is the fitting curve. Numbers refer to the specific case study.

Biogas AD plant managers were asked to provide an estimate of Opex excluding labour, feedstock cost and depreciation. Figure 6-3 indicates that data points relative to Opex were more scattered than data points of Capex in Figure 6-2. Estimates for total Opex seemed more susceptible to higher variability due to site-specific financial arrangements between the farm and the AD plant. For instance, the biogas plant manager of Case Study 6 reported that cash flow relative the biogas plant operations was kept almost neutral to reinvest profits into the farm thanks to specific arrangements and different types of business organizations.

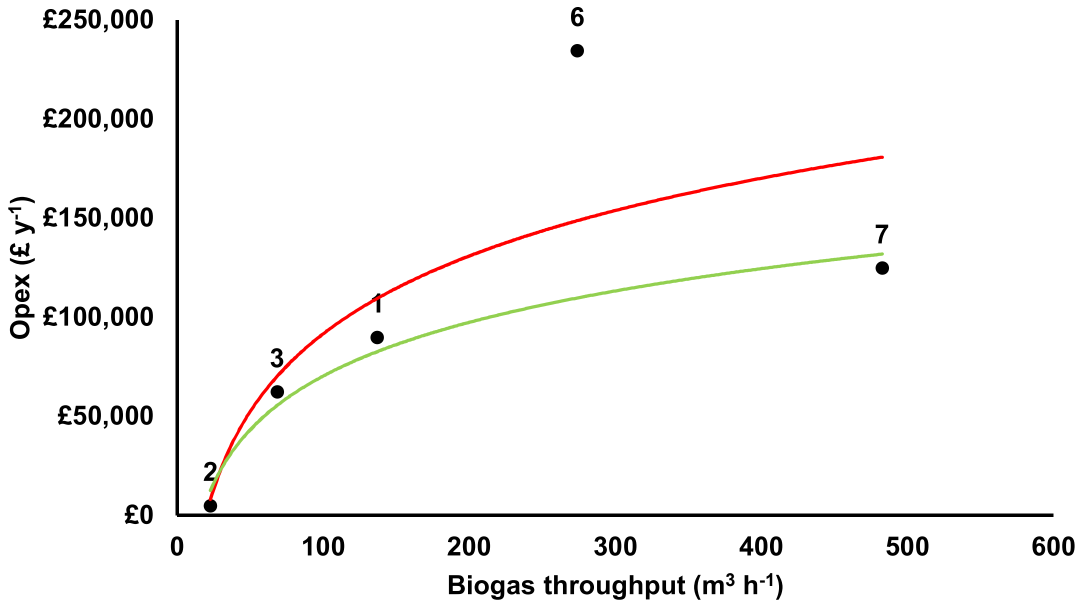


Figure 6-3: Operational expenditure of agricultural biogas plants from the case studies as a function of biogas throughput; numbers refer to the specific case study. Black dots represent data points with number 6 being an outlier. The red line is the fitting curve with the outlier and the green line is the fitting curve without the outlier.

Data points representative of Opex versus biogas throughput were fitted with a trend line represented by a red line in Figure 6-3 and described by the logarithmic equation that follows:

$$Opex = 56{,}639 \times ln(BHT) \; - \; 169{,}190$$

Equation 6-3

$$R^2 = 0.6255$$

Data point number 6 in Figure 6-3 diverged noticeably from the trend line. If this point is considered an outlier and removed it from the analysis, the power equation that fits data becomes the following:

$$Opex = 39{,}110 \times ln(BHT) \; - \; 109{,}810$$

Equation 6-4

$$R^2 = 0.9731$$

6.2.2. Transportation of feedstocks

At small to medium scale plants, there was almost no transportation involved to bring feedstock to the site since the digester was fed directly with slurry from the barns. At large biogas installations, feedstocks were transported by trucks or pipelines, where this was viable. For instance, cattle slurry was transported to the site by trucks in case of study 5 whereas in Case Study 4 a one mile long pipeline connected the dairy farm to the AD plant.

The majority of agricultural feedstocks including manures, silages and crop residues were sourced within 5-8 miles from the AD plant, except from a considerable fraction of silages in Case Study 4 that originateed approximately 30-35 miles away from the plant. Case Study 4 stood out from the rest as a large scale biogas installations utilizing a rich mix of feedstocks with high biogas yields such as whey permeate and Delactose Whey Concentrate (DWC). This allowed them to source these feedstocks from suppliers that were located as far as 300 km from the site.

6.2.3. Digestate management

Digestate is spread on farmland nearby the AD plant, usually on land owned or rented by the farm between March and October or all year round when this is permitted. From the case studies and conversations with biogas plant managers, it emerges that the availability of land on farm to spread digestate is one of the key decision making criteria to invest in AD.

Environmental regulations will likely force farmers to invest in lagoon or storage covers in the near future. For instance, in Case Study 4 the Environment Agency has required to cover the lagoon that stores liquid digestate. Moreover, the owner of AD plant of Case Study 7 argues that this is going to be soon a requirement for manure and digestate storage.

Digestate is separated into a liquid and solid fraction in Case Studies 1, 2, 6 and 8. The liquid fraction is kept in tanks for short term storage (i.e. couple of weeks in most cases) and then in open-air lagoons for long time storage. Transportation to fields is by tanker or umbilical and spread to land via either dribble bar, spraying plate or injection within 5 miles from the plant at disposal costs ranging between £1.7 and £3.5 per tonne.

The solid fraction is stored on site in heaps then transported to fields by tractor with trailer and spread to land via either dribble bar, spraying plate or injection within 5 miles from the plant at disposal costs ranging between £1.75 and £5 per tonne. Digestate is not separated in Case Studies 3, 4, 5 and 7. In this case the whole digestate is spread within 10 miles from the plant at disposal costs ranging between £2.50 and £3.50 per tonne

6.2.4. Fertiliser savings

Fertiliser savings reported in the questionnaire by biogas plant managers varied considerably within a broad range of values between approximately £0 y^{-1} and £100,000 y^{-1}. In Figure 6-4 fertiliser savings were plotted against total nitrogen content expressed as kg of N per wet tonne in the feedstock mixture. Data points relative to Case Study 4 and 8 were not available since the operators were not able to provide any estimates.

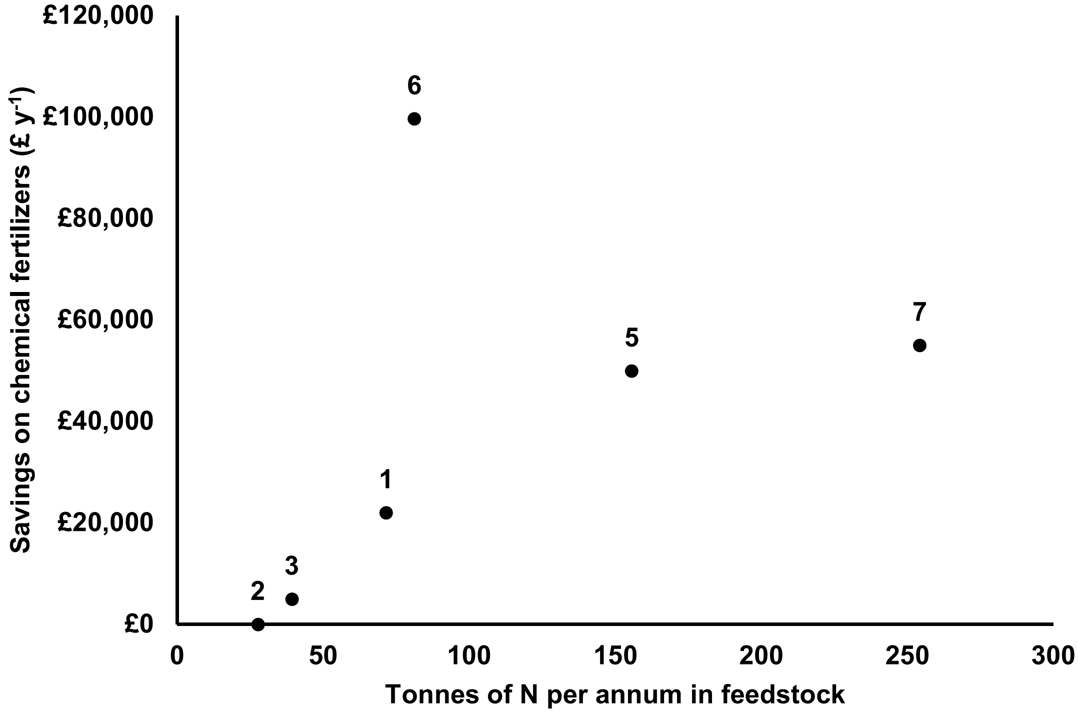


Figure 6-4: Savings on chemical fertilisers usage due to replacement with digestate as an organic fertiliser. Numbers refer to the specific case study.

The question formulated in the questionnaire did not specify the use of a precise methodology to estimate fertiliser savings. Therefore, respondents were left with a certain degree of subjectivity in answering. The outlier of Case Study 6 in Figure 6-4 relates to the fact that fertiliser savings reported by plant managers and operators were estimated with different methods.

The main difference stems from whether they take into account the total nitrogen in the digestate or only the fraction of readily available nitrogen. Since manures and slurries are spread to land as fertilizers anyway, the net financial savings attained thanks to spreading of digestate should be calculated by subtracting the fertilizer financial value associated with digestate from thefertiliser financial value of raw manures utilized in the AD. Data point 6 stands out as an outlier, hence it was removed from the analysis. It emerged a clear trend between fertiliser savings and total nitrogen in the feedstock mix.

The majority of the biogas plant managers reported improvements in soil health and crop yields. They stated that the digestate was particularly good at increasing the organic matter of the soil, improving microorganism population in the soil and plant nutrient uptake rate. The plant owner of Case Study 2 and the operators of Case Study 5 were not able to tell any difference between pre and post AD yet since the plant had only been in operations for two years.

6.2.5. Heat usage

Equation 6-5 presents the heat balance estimated at the CHP unit for each plant:

$$q_{wasted} = q_{total} - q - q_{used}$$

Equation 6-5

Where:

- q_{total} is either given as direct reading by the plant manager or it is estimated according to the biogas throughput and thermal efficiency of the CHP unit
- q is the heat needed to keep the digester at the set temperature
- q_{used} is the fraction of energy that is utilised to meet local heat demands.
- q_{wasted} is the heat that cannot be utilized

Heat end uses resulting from the interviews conducted with biogas plant managers and operators include:

- Hot water and heating for on farm households.
- Hot water for the dairy farm.
- Hot water for a swimming pool.
- Process heat for cheese production.
- Drying of logs.
- Drying of paper sludge.
- Drying of maize silage for animal bedding.
- Drying of animal fodder.
- Pre-heating of slurry in the preparation pit.

In cases where the operator did not provide a reading or an educated estimate of the heat required to meet demand, this was calculated according to the following assumptions:

- Household heating was based on the average domestic consumption of 12,000 kWh_{th} y^{-1}. [1]
- Biogas replaced kerosene for heat production.
- The water of a hypothetical swimming pool of 25 m long by 12 m wide by 3 m deep was kept at a temperature of 25 °C throughput the year with average air temperature of 15 °C.[2]

Figure 6-5 shows that the fraction of excess heat recovered on farm was limited unless the AD plant was located in proximity of end users requiring process heat or drying. In this case, excess heat could be fully recovered and utilized improving the profitability of the operations. For instance, drying turned out a practical and effective method to use up the heat recovered from the CHP unit as illustrated in Case Studies 3, 7 and 8. Similarly, Case Studies 2 and 4 featured a higher proportion of heat recovered thanks to the process heating required by the cheese factory. With the phasing out of the FIT, new biogas plants will have to be located in the proximity of heat demand to make AD viable.

[1] https://www.ofgem.gov.uk/gas/retail-market/monitoring-data-and-statistics/typical-domestic-consumption-values
[2] https://www.engineeringtoolbox.com/swimming-pool-heating-d_878.html

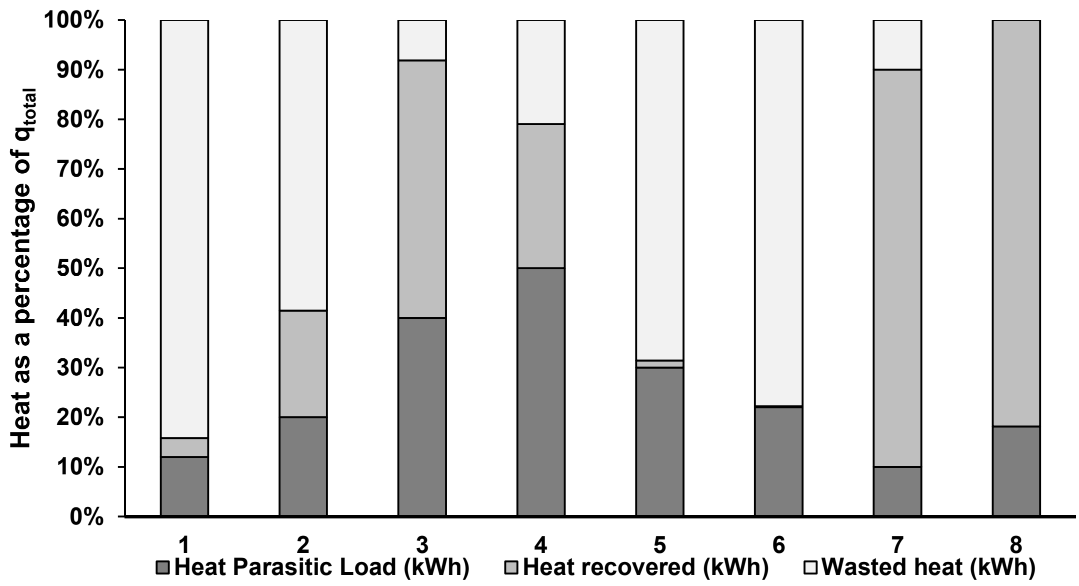


Figure 6-5: The extent of heat usage varies considerably at the AD plants between case studies mainly depending on the proximity of heat end users for processing and drying. Each number refers to a case study.

6.3. Evaluation of biogas plant efficiency

Three different bio-methane potentials were calculated from data collected from the eight case studies and presented in Appendix A:

- *BMP_{plant}*: it was the effective bio-methane potential calculated via Equation 6-6:

$$BMP_{plant} = \frac{Biogas\ throughput \times Methane\ content}{VS_{total}}$$

Equation 6-6

  Terms in Equation 6-6 referred to data directly provided by the biogas plant manager. Biogas throughput was the annual biogas production, methane content was the percentage of methane in biogas and total VS_{total} was the total VS added to the digester.

- *BMP_o:* it was the ultimate bio-methane potential calculated by applying the standard BMP_o illustrated in Table A-3 in Appendix A.12. The calculation of BMP_o from standard values published in the literature helped to compare BMP_{plant} with a benchmark. For a given feedstock mixture, the BMP_o was calculated via Equation 6-7:

$$BMP_o = \frac{\sum_{i=1}^{n} BMP_o^i \times VS_{total}^i}{VS_{total}}$$

Equation 6-7

- BMP_{th}: it was the theoretical bio-methane potential according to Buswell equation, which is 0.350 m^3 STP CH_4 kg^{-1} of COD removed. Table A-3 in Appendix A.12 shows the theoretical BMP of the feedstocks utilized at biogas installations. The calculation of the maximum theoretical bio-methane potential was needed to check if the data given in the questionnaire are meaningful and within theoretical limits.

The bar chart in Figure 6-7 compares BMP_{plant}, BMP_o and BMP_{th} for each Case Study including the estimation of the VS destruction efficiency indicated by black dots. The ratio between the BMP_{plant} and the BMP_{th} is a proxy for the extent of COD removal. This was the lowest for the AD plants showing the highest share of cattle manure in the feedstock mix. For instance, in Case Studies 2 and 8 the fraction of cattle manure in the total influent VS was respectively 88 and 90 % leading to estimated COD removal of 37 and 34 %. The efficiency tended to increase with higher share of crops and other waste in the mix reaching 75 and 78 % in Case Studies 4 and 6.

Case Studies 5 and 7 represented exemptions to this trend owing to inefficiencies in the biology of the digester in the former and a significant share of poultry manure in the mix in the latter. This trend was consistent with findings in the literature from other similar studies on COD removal and VS destruction efficiency in biogas plants (Ruile *et al.*, 2015; Ahlberg-Eliasson *et al.*, 2017). However, the findings of these studies were based on direct measurements of volatile solids in samples of feedstock mixtures and digestate.

All BMP_{plant} calculated by Equation 6-6 from data provided by operators were lower than the corresponding estimated maximum theoretical values. Values of BMP_{plant} were comparable with those of BMP_o, however several factors determined the mismatch between BMP_{plant} and BMP_o in some cases leading to BMP_{plant} being higher than BMP_o as illustrated in Figure 6-6

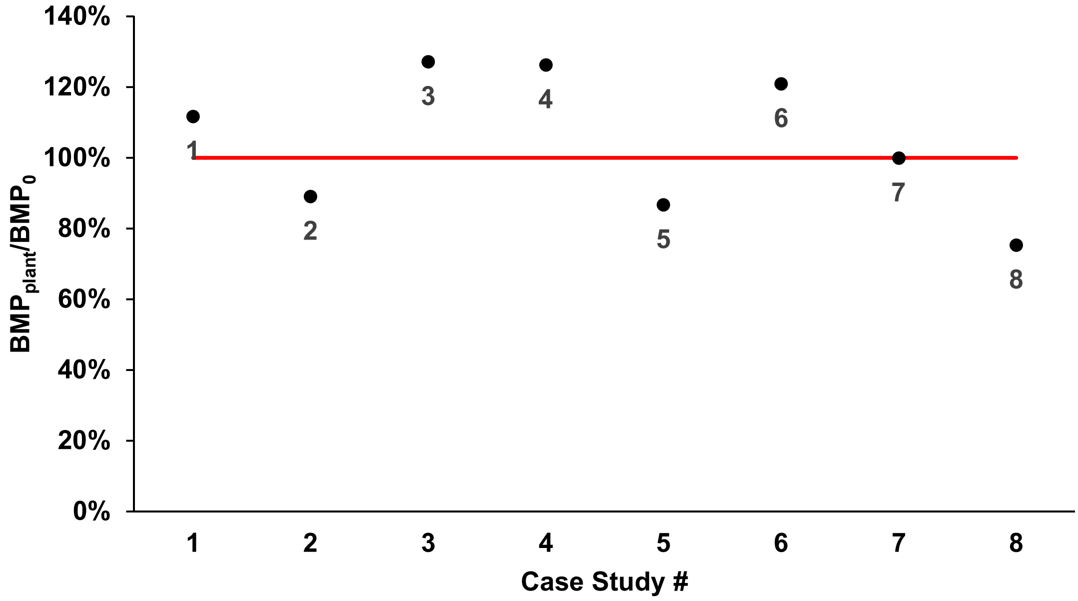


Figure 6-6: The distance of the data points from the red line indicates the degree of uncertainty inherent in the comparison between BMP_{plant} and BMP_0

BMP_o is measured in batch tests at standard conditions of 35 °C for retention times typically between 30 and 60 days. Even for the same substrate BMP_o varies significantly (Labatut et al., 2011). In addition, anaerobic digestion in the case studies examined occurred at temperatures between 38 and 42 °C, which were slightly higher than standard temperatures of *BMP* tests. There was also an element of confidence in the accuracy of the data on biogas throughputs provided by the biogas plant manager and operators. The estimation of the BMP_o values for the feedstock mixtures examined in the case study should be based on measurements taken on samples, not on literature values for more realistic comparisons.

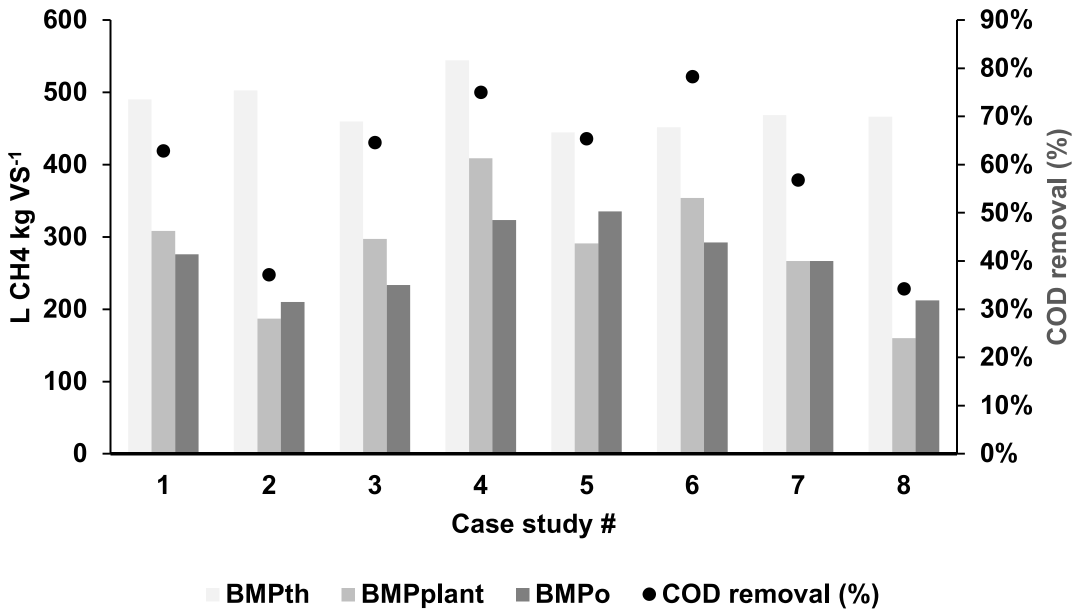


Figure 6-7: Comparison of the BMPs calculated in the evaluation of the performance of each AD plant.

Figure 6-8 illustrates the relationship between the BMP_{plant} and the percentage of volatile solids stemming from crops and waste in the feedstock mix. The graph outlines the expected trend that for increasing share of crops and waste in the mix the biogas yield rises. There were physiological variations in biogas yields between plants showing the same share of cattle manure in the feedstock mix. This becomes more evident as the share of cattle manure in the mix shrinks as in Case Studies 4 to 7. There were several reasons underlying these variations in biogas yields.

Firstly, cattle manure characteristics varied significantly and, by consequence, biogas yields. Secondly, plants operated at different efficiencies, organic loading rates, slightly different temperatures and mixing systems. These parameters had a major impact on the final biogas yield achieved. Thirdly, the share of wastes with high biogas yields in the mix had a big impact on the final biogas throughput. For instance, in Case Study 7 almost 47 % of total VS in the feedstock mix utilised derived from poultry manure having a lower biogas yields than vegetable, fruit, bakery or dairy wastes.

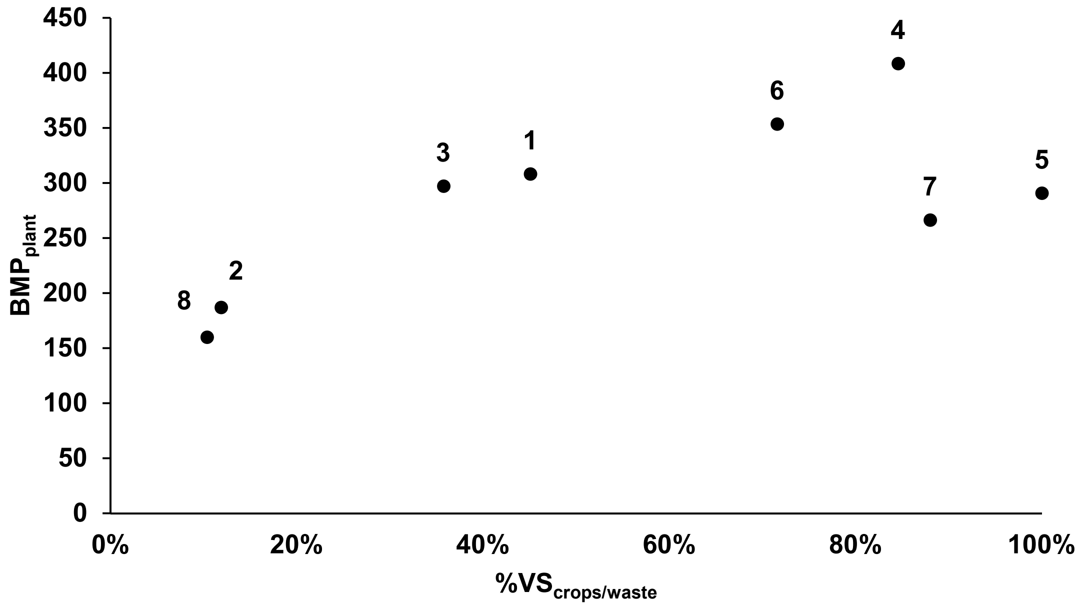


Figure 6-8: Relationship between the proportion of crops in the feedstock mixture and BMP achieved by the AD plants in the case studies. Each number refers to a case study.

Despite having the lowest share of cattle manure in the mix, Case Studies 5 and 7 seemed to underperform. The plant operator of caste study 5 reported that the current retention time was not sufficient to ensure the complete biodegradation of the organic material in the crops. Moreover, the AD plant had just under one year of operations and they had some issues with silage quality. They planned to extend the retention time by installing an additional tank. The high *VS* destruction achieved in Case Studies 4 and 6 was the result of higher fraction of highly biodegradable substrates such as food residues and energy crops in the feed.

Figure 6-9 represents the relationship between BMP_{plant} and the estimated HRT. The graph indicates that biogas yield increases with HRT although data points are significantly scattered across a wide range of HRTs. This was mainly due to the uncertainty associated with the estimation of the HRT and, to a lesser degree, confidence in the values of biogas throughputs provided by the operators. HRT was calculated as the ratio between the volume of the main digester and total annual wet tonne of feedstock utilized.

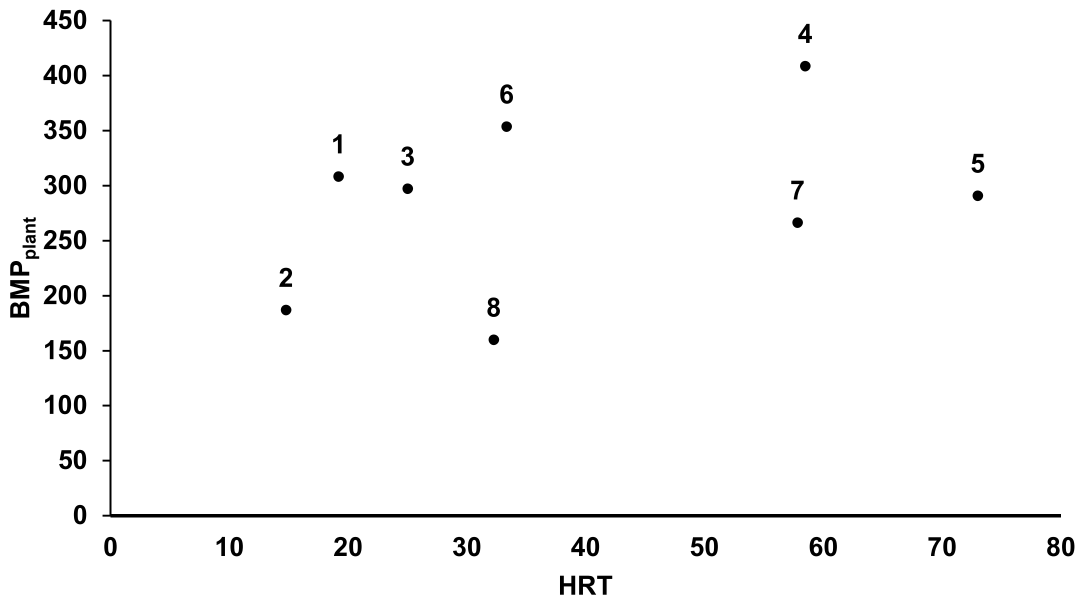


Figure 6-9: Relationship between HRT and the BMP achieved by the AD plants in the different case studies. Each number refers to a case study

6.4. Kinetic model evaluation

Here results from the application of the non-linear least squares solver in MATLAB® to the primary data on BMP_{plant}, HRT and $VS_{\%}^{crop/waste}$ collected from the eight case studies were presented. The aim was to find four parameters, $BMP_o^{crops/waste}$, BMP_o^{manure}, $k_{crops/waste}$ and k_{manure} that best fit the curve described in Equation 2-17 in Section 2.2.

This analysis set out to reproduce the methodology presented by Linke *et al.* (2013). They fitted the equation describing the AD kinetic with data collected from 24 German biogas plants fed with cattle manure and energy crops. In this case there were 8 data points for curve fitting. Table 6-9 shows a comparison of the outcome of data analysis from the eight case studies and the German study by (Linke *et al.*, 2013).

Table 6-9: Comparison between results from the curve fitting exercise and the model by (Linke *et al.*, 2013).

Parameter	This work	Linke *et al.* (2013)	Units
$BMP_0^{crops/waste}$	473.00	420.00	L CH_4 kg VS^{-1}
BMP_0^{manure}	186.00	270.00	L CH_4 kg VS^{-1}
$k_{crops/waste}$	0.02	0.20	d^{-1}
k_{manure}	0.54	0.20	d^{-1}

Eight data points represented a small sample to extrapolate a meaningful trend, given also the uncertainty associated with the primary data collected and the estimated HRT. Future work should put effort to extend this investigation to include more data points via direct site visits and interviews with plant managers and operators or phone/postal/online surveys.

Despite the limitations of this study, kinetic parameters attained were reasonably close to values published in the literature for the same substrates. For instance, Vavilin *et al.* (2008) showed that first-order rate kinetic coefficients of hydrolysis were 0.13 for cattle manure and between 0.009 and 0.094 for crops and crop residues without pre-treatments. While the value for $k_{crops/waste}$ was within the expected range of values, the estimated k_{manure} was higher than what was reported in the literature.

BMP_o^{manure} compared well with literature data. For instance, KTBL database indicateed a value of 181 L CH_4 kg VS^{-1} for cattle slurry and 209 L CH_4 kg VS^{-1} for cattle manure. The ultimate $BMP_o^{crops/waste}$ and BMP_o^{manure} estimated via Equation 2-17 in section 2.2 referred to infinite HRT approaching the maximum *BMP*. Nonetheless, $BMP_o^{crops/waste}$ seemed to overestimate BMP_o reported in the literature for crops. This was due to the quality of primary data collected as well as the small size of the sample used in this study.

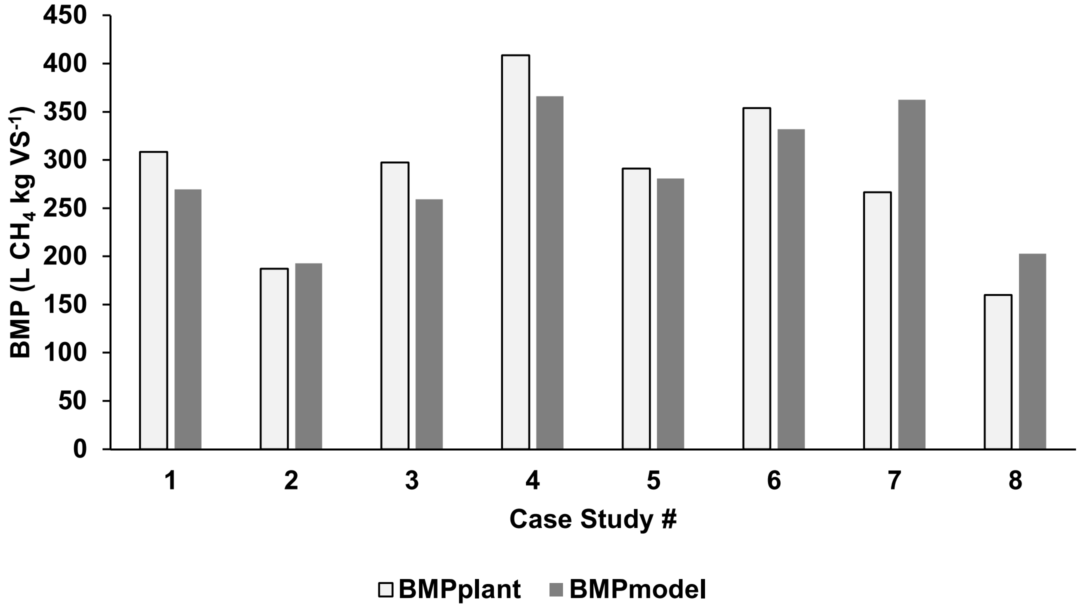


Figure 6-10: Comparison between model predictions of BMP according to the kinetic model fitted via non-linear curve with estimated parameters shown in Table 6-9 and BMP_{plant} values as reported from biogas plant operators for all Case Studies. This plot is indicative of the accuracy of the BMP predictions of the kinetic model developed in this study.

Error! Reference source not found. Figure 6-10 compares BMP predictions of the kinetic model fitted via non-linear curve to estimate four parameters in Table 6-9 and BMP_{plant} values taken directly from biogas plant operators for all Case Studies. This comparison was representative of the accuracy of the kinetic model. Percent variation between BMP predictions and BMP_{plant} values was calculated with Equation 5-1. Five out of eight case studies showed a negative percent variation meaning that the model tend to slightly underestimate BMP_{plant}, as it can be seen visually in Figure 6-10. The calculation of percent variation for Case Studies 7 and 8 returned positive large values of respectively 36.0 % and 26.7 %. The reasons why this occurred for Case Study 7 was already discussed in the previous section whereas a value of HRT of plant in Case Study 8 larger than the optimal value, which kinetics would suggest, could be the main cause of divergence.

Figure 6-11 plots Equation 2-17 with parameters estimated via non-linear curve fitting function in MATLAB® from the eight data points. Each curve describes the BMP as a function of HRT for various fractions of volatile solids from crops and waste in the feedstock mix ranging from 0 to 1. As this fraction increases, the overall BMP of the mix increases linearly while the first order degradation rate decreases. This is clear from shape of the curve flattening out as the fraction of VS from crops and waste rises, implying that a higher proportion of crop material in the mix undergo hydrolysis slowing down the overall degradation rate. However, it seems that the model penalizes degradation rates for mixes with high share of crops in the mix.

Despite $k_{crops/waste}$ being within the range of values reported in the literature, this was still lower than it should be in practice since crop silages underwent some degree of pre-treatment before anaerobic digestion via chopping and ensiling. For instance, Herrmann *et al.* (2016) estimated first order degradation rates from laboratory experiments on a wide range of crop silages utilised at German biogas installations with an average value of 0.187 d^{-1}.

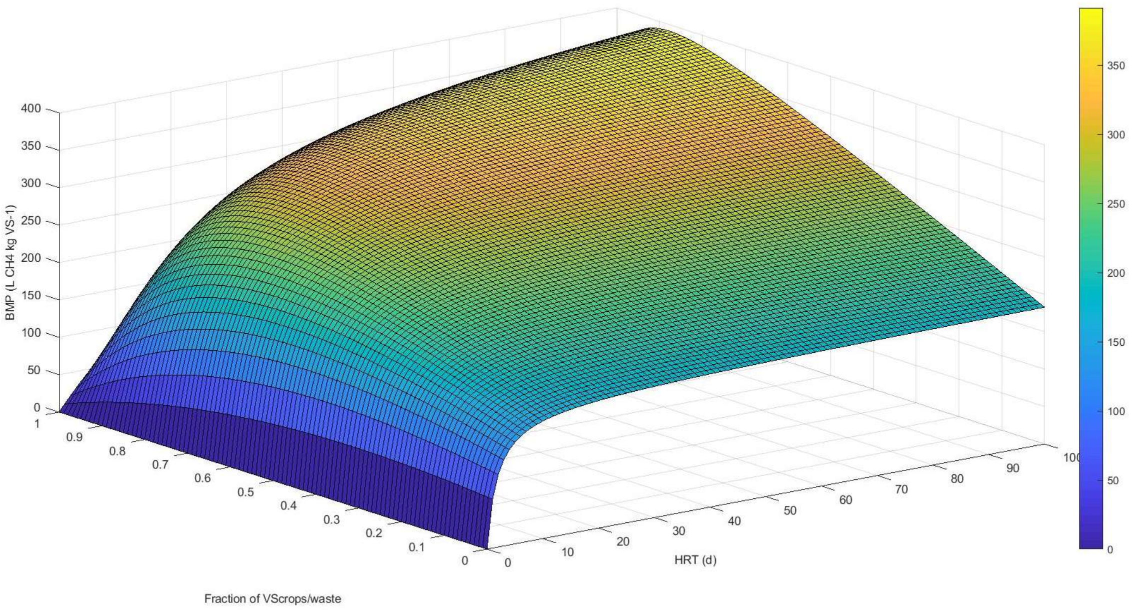


Figure 6-11: This plot shows the independent variable BMP as a function of HRT and percentage of crops in total volatile solids (*%VS_{crops}*). The coloured bar indicates increasing values of BMP from blue to yellow. Highest BMP are achieved for long HRT and higher %VS_{crops}

Figure 6-12 plots Equation 2-17 with parameters estimated according to the dataset by Linke *et al.* (2013). They found a lower $BMP_o^{crops/waste}$ of 420 L CH_4 kg VS^{-1}, a higher BMP_o^{manure} of 270 L CH_4 kg VS^{-1} and both the kinetic parameters of 0.2 d^{-1}, from a larger sample of 24 data points. While the kinetic constants were closer to the values published in the literature, they still did not reveal the different degradation rates inherent to manures and crops. This can be shown with the example illustrated in Table 6-10.

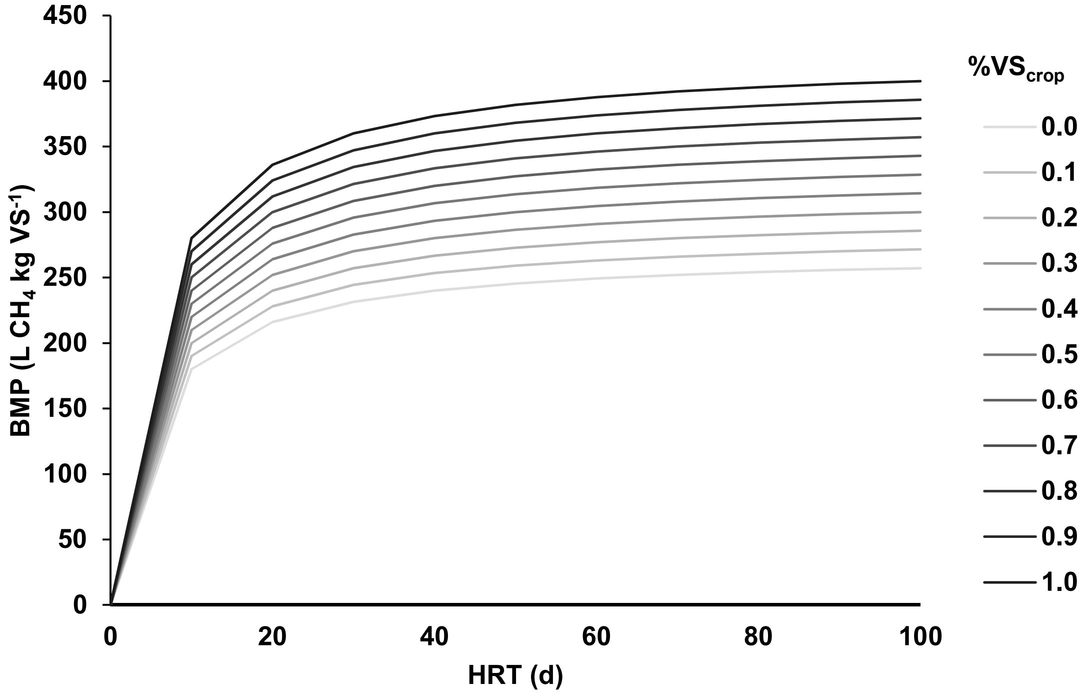


Figure 6-12: Values of *BMP* for various fractions of *VS* in the feedstock mixture and HRT as calculated according to Linke *et al.* (2013) with the four parameters from Table 6-9.

The ratio between *BMP* and BMP_o^{Mix} in Equation 2-17 is indicative of the degree of degradation of the of the biodegradable fraction in the feedstock mix. Anaerobic digesters are designed to achieve a minimum degradation efficiency between 0.8 and 0.9. Therefore, various HRTs were estimated for different proportions of crops to achieve a minimum VS destruction efficiency of 0.9. Since the degradation rate constants were the same for manures and crops in the model by Linke *et al.* (2013), the HRT required to achieve this destruction efficiency would not change with the proportion of crops in the mix.

Table 6-10: Comparison between the model of Linke *et al.* (2013) and this work, based on the same equation but with different parameter sets.

Biodegradable VS destruction = 0.9	Linke *et al.* (2013)		This work	
Percentage of crops In total VS (%)	HRT	BMP	HRT	BMP
0	45	243	17	167
20	45	270	21	220
50	45	310	32	297
70	45	337	51	348
85	45	358	93	388
100	45	378	426	425

HRT should increase with the increase of the proportion of crops in the mix to achieve the same VS destruction efficiency. This trend did not emerge from the model with parameters estimated by Linke *et al.* (2013). The model did reflect this trend, however it predicted a degradation rate for mono-digestion of cattle manure faster than typical values found in the literature, and a degradation rate for mono-digestion of crops slower than expected from literature values. This led to the estimation of extremely high HRTs in the case of mono-digestion of crops.

Despite these drawbacks, this model was representative of the kinetics of AD plants with proportions of crops in total VS lower than 80 %. This is likely to be the future trend in the AD industry since regulations in the UK have mandated that at least 50 % of the biogas yield must come from waste streams to be eligible for subsidies. This is equivalent to have at least 50 % of volatile solids in the mix stemming from cattle manure.

6.5. Financial model evaluation

The the Excel-based evaluation tool of biogas production developed in this study was evaluated against primary data associated with Capex, Opex, EPL, HPL and fertiliser savings collected from the case studies. The performance of this model of AD plants with CHP units was compared to financial data provided by plant managers and operators from real sites. Case Studies 4 and 5 were excluded since they upgraded biogas, rather than utilising CHP. Case Study 8 was also excluded since the biogas manager did not provide any financial data. Therefore, the assessment of model predictions on Capex, Opex EPL, HPL and fertiliser savings included data only from Case Studies 1, 2, 3, 6 and 7.

The logic underpinning model calculations for comparison with primary data from Case Studies is described in detail here:

- The model takesthe inputs on wet tonne per annum by feedstock type in the mixture as illustrated in Tables from Table 6-1 and Table 6-8
- It calculates the share of cattle manure in total volatile solids as percentage This value is instrumental to calculate k_{mix} and BMP_0^{mix} in Equation 2-17.
- TEquation 2-17 with parameters estimated from data illustrated in Table 6-9 is solved for HRTs corresponding to the values estimated for Case Studies 1, 2, 3, 6 and 7 to calculate *BMP*.
- Biogas throughput and CHP electrical output (W_{CHP}) were calculated according to Equation 4-8 and Equation 4-9. Values for Biogas throughput and W_{CHP} from model simulations are presented in Appendix D.
- Total volume of the main digester (V_{tank}) was calculated according to the method described in Section 4.2. Values for V_{tank} from model simulations are presented in Appendix D.
- The heat exchanger size is estimated with the method presented in Section 4.4.1

- Heat parasitic load (*HPL*) and Electric parasitic load (*EPL*) were calculated respectively with methods described in Section 4.4.2 and Sections from 4.4.3 to 4.4.6. Values for HPL and EPL from model simulations are presented in Appendix D.
- Capex is calculated by solving equations illustrated in Table 4-3. $P_{capacity}$ in Table 4-3 is the capacity of the feeding pump that was estimated assuming that the volume of the main digester (V_{tank}) can be emptied in 24 hours. *Capacity* in Table 4-3 is the daily loading rate of the solids feeder that was estimated assuming a typical value for silage density of 550 kg m^{-3}. *Ton* in Table 4-3 is the amount of wet tonnes ensiled in a year.
- Opex is calculated according to the methodology described in Section 4.7.
- Fertiliser savings are calculated according to Section 4.5.

Table 6-11 shows the outputs from the model simulations. Opex here refers to total operational expenditure excluding labour, feedstock and transportation costs.

Table 6-11: Model outputs resulting from applying the feedstock mixtures from the case studies.

Case Study	Biogas throughput (m^3 h^{-1})	HPL (%)	EPL (%)	Capex	Opex	W_{CHP}	Fertiliser savings
1	122	30.00	12.00	£1,082,484	£47,133	268	£17,761
2	23	68.00	10.00	£473,516	£20,302	51	£6,634
3	57	37.00	21.00	£799,032	£34,619	124	£9,638
6	242	16.00	7.00	£1,655,467	£70,180	531	£22,360
7	633	8.00	4.00	£2,695,304	£133,018	1388	£55,823

The root mean square error (*RMSE*) was calculated to compare the outputs from the model with primary data from the case studies. The comparison was based on the following equation:

$$RMSE = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{n}\left(\frac{x_i - y_i}{x_i}\right)\right)^2}$$

Equation 6-8

Where:

- x_i is the value of the variable as estimated by the model.
- Y_i is the value of the variable as gathered from the biogas operator/manager.
- n is the number of data points.

The model showed good predictive skills of Capex while its performance deteriorated for Opex and fertiliser savings. Nonetheless, the *RMSE* values calculated for Opex and fertiliser savings were still acceptable. This demonstrated that the predictability of these two variables in financial models of biogas plants was challenging since their estimation was very context specific. Calculated values of *RMSE* illustrated in Table 6-12 referring to Opex and fertiliser savings included the outlier from Case Study 6.

Table 6-12: Values of RMSE calculated by comparing model outputs with data from case studies.

Variable	*RMSE*
Capex	0.32
Opex	1.23
Fertiliser savings	1.49

The solid line in red in Figure 6-13 is the best fitting curve of the data points in black referring to Capex from the case studies. The solid line in blue shows the best fitting curve estimated from data points in red resulting from model outputs. Unlikely the data points on Capex from the case studies, which were best fitted by a logarithmic curve, the model outputs were best described by Equation 6-9:

$$Capex = 93{,}303 \times BHT^{0.521}$$

Equation 6-9

$$R^2 = 0.9973$$

This plot showed that the model tended to slightly overestimate Capex for small-scale systems with biogas throughputs lower than approximately 50 m^3 h^{-1} whereas it tended to slightly underestimate Capex of bigger systems.

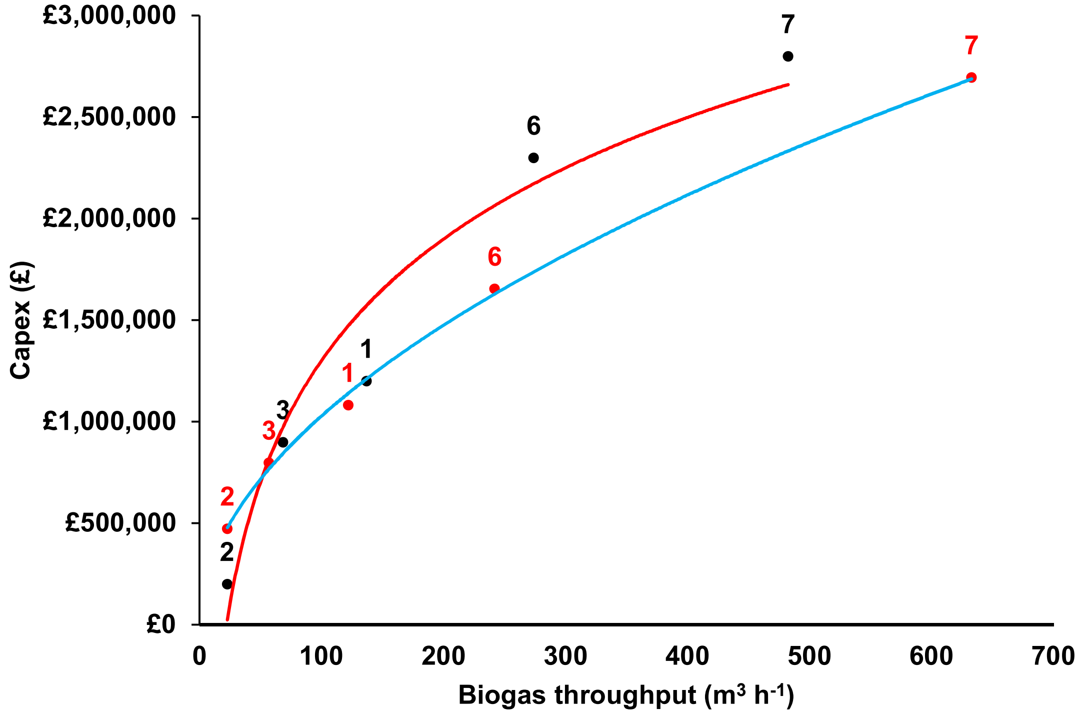


Figure 6-13: Comparison of Capex data from the case studies (black dots) with predictions from model simulations (red dots). Red line is the line of best fit to data points from case studies whereas blue line is the line of best fit to data from model simulations. Numbers refer to Case Studies.

The same trend was observed for Opex. Figure 6-14 shows three different solid lines. The red and green lines are respectively the best fitting curve for data points in black on Opex from the case studies with outlier (point 6) and without outlier. The blue solid line shows the best fitting curve estimated from the model simulations. Unlikely data points from the case studies, the model outputs were best described by the following power equation:

$$Opex = 3{,}516 \times BHT^{0.5544}$$

Equation 6-10

$$R^2 = 0.9938$$

The model tended to slightly overestimate Opex for small-scale systems and slightly underestimate Opex for bigger systems.

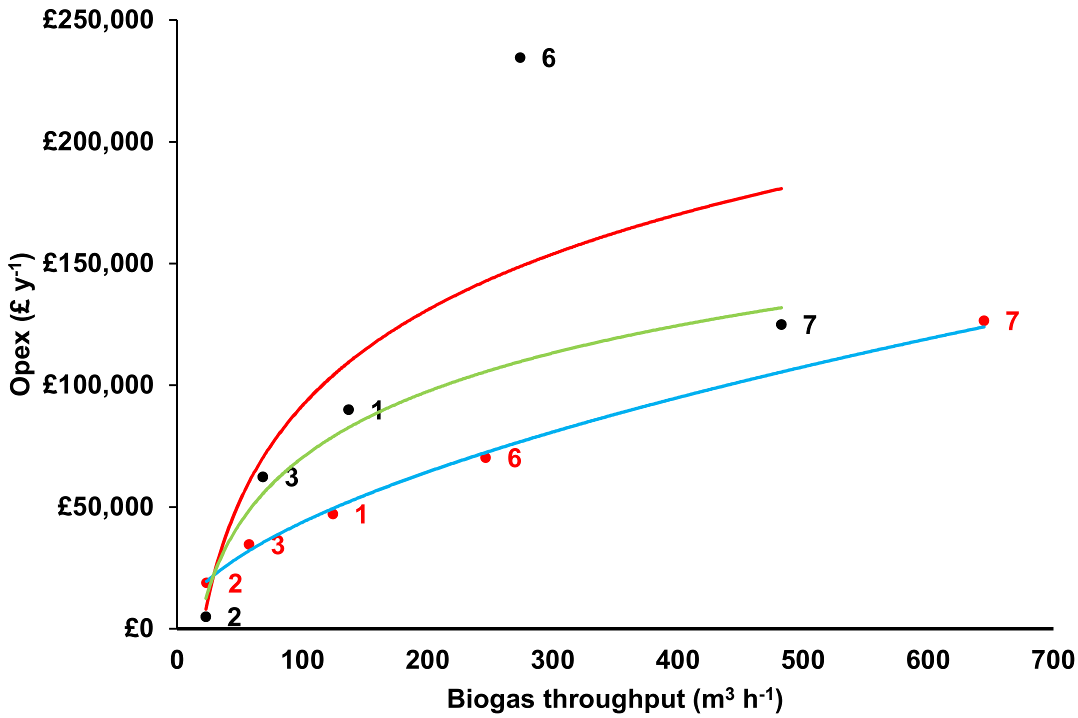


Figure 6-14: Comparison of Opex data from the case studies with (red line) and without (green line) the outlier, and Opex predictions from model simulations (blue line). Black dots represent data points from the case studies; red dots represent data points from model simulations. Numbers refer to Case Studies.

6.5.1. Digestate management

Digestate was spread on farmland nearby the AD plant, usually on land owned or rented by the farm between March and October or all year round when this was permitted. From the case studies and conversations with biogas plant managers, it emerged that the availability of land on farm to spread digestate was one of the key decision making criteria to invest in AD.

Environmental regulations will likely force farmers to invest in lagoon or storage covers in the near future. For instance, in Case Study 4 the Environment Agency required to cover the lagoon that stores liquid digestate. Moreover, the owner of AD plant of Case Study 7 argued that this is going to be soon a requirement for manure and digestate storage.

Digestate was separated into a liquid and solid fraction in Case Studies 1, 2, 6 and 8. The liquid fraction was kept in tanks for short term storage (i.e. couple of weeks in most cases) and then in open-air lagoons for long time storage. Transportation to fields was by tanker or umbilical and spread to land via either dribble bar, spraying plate or injection within 5 miles from the plant at disposal costs ranging between £1.7 and £3.5 per tonne.

The solid fraction was stored on site in heaps then transported to fields by tractor with trailer and spread to land via either dribble bar, spraying plate or injection within 5 miles from the plant at disposal costs ranging between £1.75 and £5 per tonne. Digestate was not separated in Case Studies 3, 4, 5 and 7. In this case the whole digestate was spread within 10 miles from the plant at disposal costs ranging between £2.50 and £3.50 per tonne

6.6. Fertiliser savings

The evaluation of the model to estimate fertiliser savings was based on six data points, since biogas plant operators from Case Studies 4 and 8 did not provide any information on fertiliser savings. Case Study 5 was included here even though they upgraded biogas. Table 6-13 summarises the outputs from model simulations.

Table 6-13: Fertiliser savings resulting from model simulations.

Case Study	Tonnes of N per annum in the feedstock mix	Fertiliser savings
1	72	£17,761
2	28	£6,634
3	39	£9,638
5	156	£54,782
6	81	£22,360
7	254	£55,823

The red dots in Figure 6-15 illustrates model outputs while black dots are data points from case studies. Data point relative to Case Study 6 was the outlier that was not considered in the analysis. Model outputs compared well with data points from Case Studies 1, 2, 3, 5 and 7 as indicated by the *RMSE* value of 1.487 in Table 6-12.

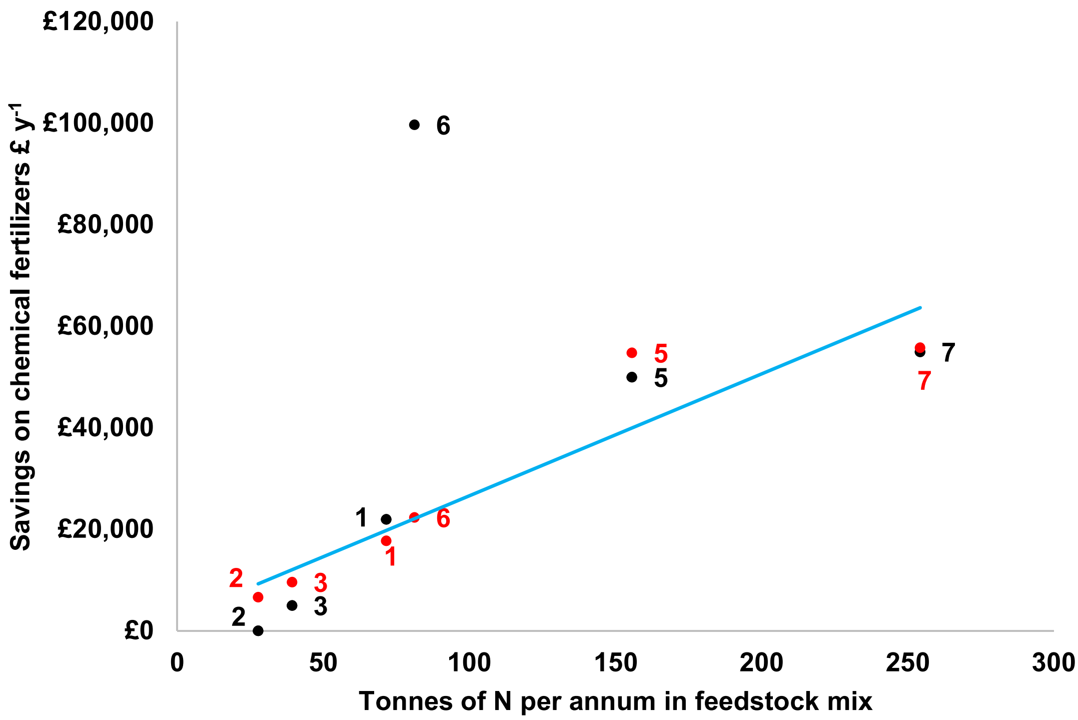


Figure 6-15: Fertiliser savings data, as reported from biogas plant managers (black dots) compared with predictions from the model simulations (red dots). Numbers refer to Case Studies

A linear trend was observed between potential fertiliser savings and total nitrogen in the feedstock mix indicated by the blue solid line in Figure 6-15 with associated equation as follows:

$$Savings_F = 240.23 \times TN_{feed} + 2{,}628.$$

Equation 6-11

$$R^2 = 0.8773$$

Where Total N is tonnes of total nitrogen in total wet tonne of feedstock mix.

6.7. Parasitic load

The estimation of heat and electrical parasitic loads was challenging due to the intrinsic variability between case studies in plant configurations as well as on the accuracy of the data provided by the plant operators and managers. Nevertheless, general trends could be identified and some meaningful conclusions could be drawn. Table 6-14 shows results from model simulations related to heat parasitic loads.

Table 6-14: Comparison between data from case studies and model outputs on heat parasitic load.

Case Study	VS (% wet weight)	Heat parasitic load (%) – Model outputs	Heat parasitic load (%) – Case studies
1	8.04%	30	12
2	5.00%	68	20
3	7.05%	37	40
6	12.64%	16	22
7	27.23%	8	10
8	10.47%	31	18

Error! Reference source not found. Figure 6-16 illustrates the heat parasitic load against VS content in the feedstock mix. This figure demonstrated that model outputs showed a noticeable trend between heat parasitic load and the total VS in the feedstock mix. This trend indicated that diluted feedstock mixes, as is in case of mono-digestion of cattle slurry, required a higher fraction of the heat output to heat up a larger proportion of water in the mix. Model outputs of heat parasitic load were fitted with Equation 6-12 as a function of VS in the feedstock mix:

$$HPL = 0.0152 \times VS^{-1.232}$$

Equation 6-12

$$R^2 = 0.9526$$

Data points from the case studies were represented by black dots in **Error! Reference source not found.**Figure 6-16 and compared with model outputs in red dots to calculate RMSE of 0.455.

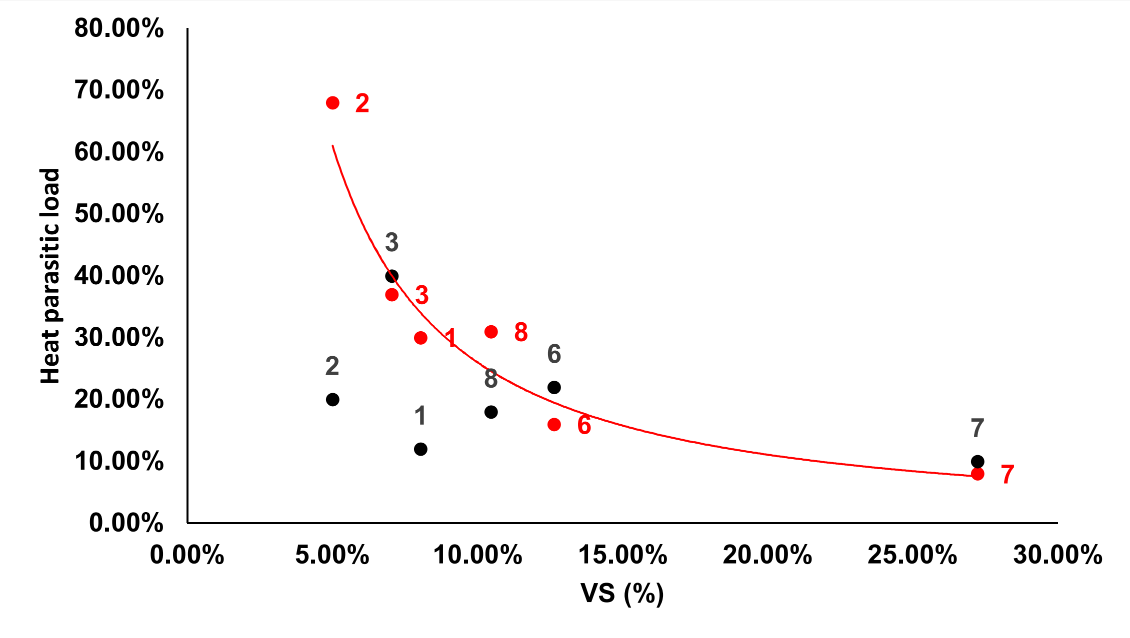


Figure 6-16: Data in black dots are from case studies and data points in red are from model outputs on heat parasitic load as a function of VS of the feedstock mix. Red line is the line of best fit to model output data points. Numbers refer to Case Studies.

Table 6-15 shows the results from the model simulations on the estimation of the electrical parasitic load compared with the corresponding data from the case studies. The data point relative to Case Study 7 were not reported since the biogas plant owner did not provide any information. Data in Table 6-15 were plotted in Figure 6-17 with black dots representing data from case studies while red dots are the model outputs.

Table 6-15: Comparison between data from the case studies and model outputs on electricity parasitic load.

		Model outputs	Case studies
Case Study	Q_{in} (wet tonne y^{-1})	Electrical parasitic load (%)	Electrical parasitic load (%)
1	26,622	12	15
2	11,125	10	4
3	14,600	21	6
6	27,375	7	7
7	30,295	4	NA
8	67,890	10	6

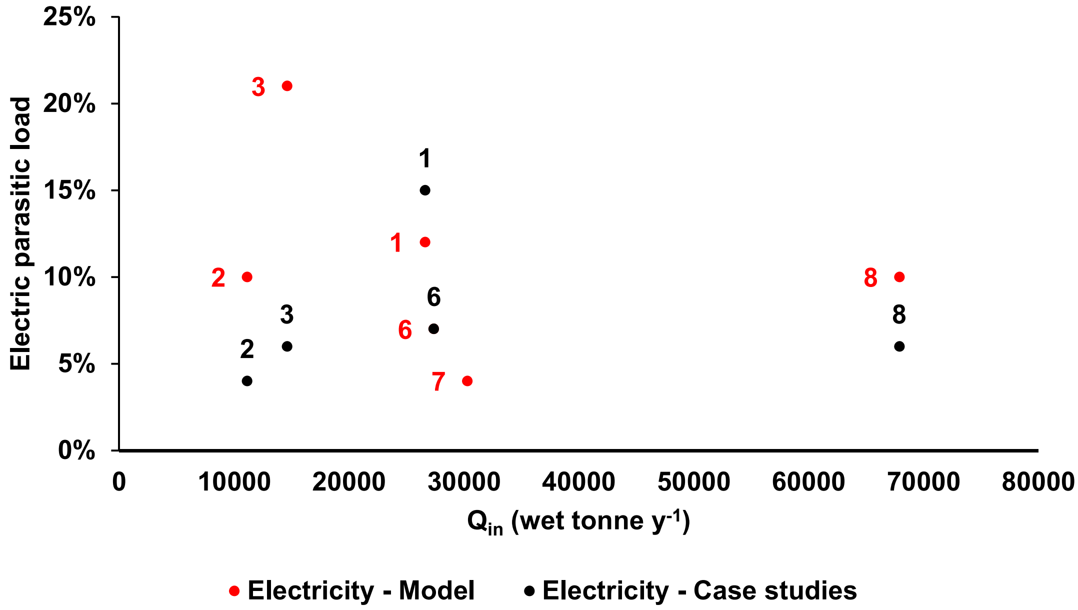


Figure 6-17: Data from the case studies are represented by black dots whilst data from model outputs are shown by red dots. The biogas plant manager was not able to provide any data for EPL of biogas plants relative to Case Study #7. Numbers refer to Case Studies.

Data points displayed in Figure 6-17 seemed to be scattered in a way that did not allow to identify any clear-cut trend. Therefore, no relationship was extrapolated from these data points. The electrical parasitic load was plotted versus the total annual wet tonne of feedstock utilized since the main factor determining the EPL calculations was flowrate. The average electric parasitic load reported by the biogas plant managers and operators was circa 8 %. Data points from the case studies represented by black dots in Figure 6-17 were compared with model outputs in red dots to calculate a RMSE of 0.467.

However, it was found that EPL showed a weak correlation with the volume of main digester (V_{tank}) as shown in Figure 6-18 according to the following equation:

$$EPL = 1.223 \times {V_{tank}}^{-0.321}$$

Equation 6-13

$$R^2 = 0.4313$$

Energy required for mixing has a major impact on the total EPL. The line of best fit shown in red in Figure 6-18 illustrates that EPL tends to diminish as the volume of the main digester increases. This entails that with increasing tank volumes biogas throughput outgrows the increase in the amount of energy required for mixing larger volumes.

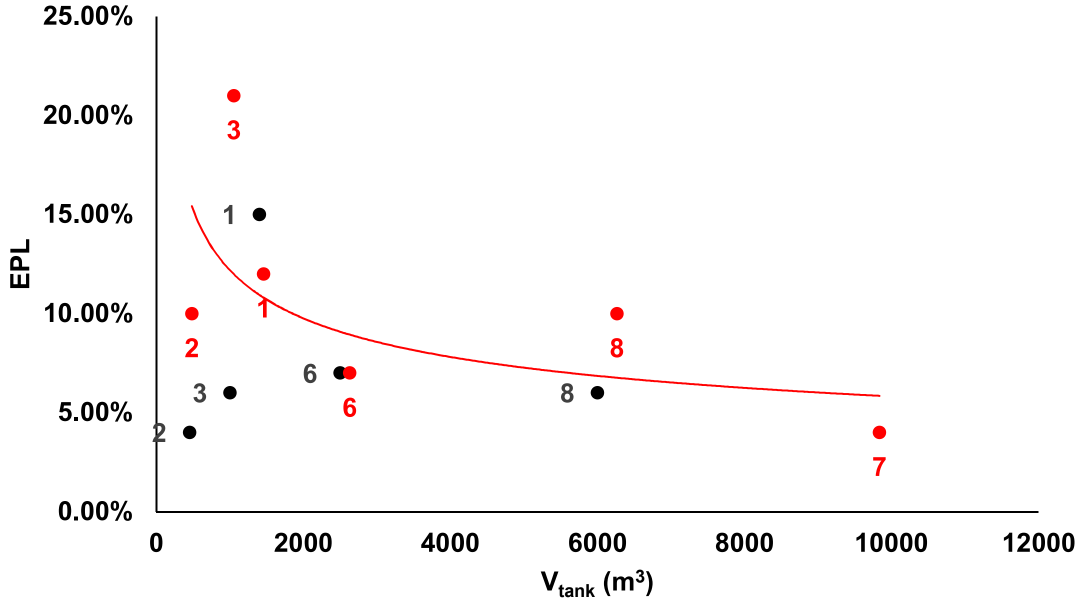


Figure 6-18: Data from the case studies are represented by black dots whilst data from model outputs are shown by red dots. The biogas plant manager was not able to provide any data for EPL of biogas plants relative to Case Study #7. Red line refers to the line of best fit to data points relative to model outputs. Numbers refer to Case Studies.

6.8. Conclusions

The following key points summarise the findingsfrom the analysis of the case study:

- In the region the majority of on farm biogas plants utilized a mix of cattle manure and crop-based feedstocks to produce biogas for cogeneration of electricity and heat. Facilities were located next to the animal barns.
- Feedstocks were sourced within the farm and digestate was spread back to farmland. Transportation of feedstocks and digestate off-farm was negligible. This enabled to close the loop of nutrients within the same farm.
- Availability of land for digestate spreading and costs of feedstock supply were the most important factors influencing the decision making process of AD investments.
- Feedstocks were transported within 5-8 miles radius from the AD plant. However, larger installations with biogas throughputs exceeding 900 $m^3 h^{-1}$, which upgraded biogas to gas to grid, were the exception with feedstocks transported over longer distances.
- Data points on Capex and Opex of CHP AD plants as a function of the hourly biogas throughput fitted well with a logarithmic trend line.
- Digestate was spread on farmland within 5 miles radius from the AD plant in spring, summer and early autumn with spreading costs ranging between £1.75 and £5 per wet tonne.
- Savings on manufactured fertilisers reported by the biogas plant managers varied remarkably from £0 to nearly £100,000 per annum. The estimations provided were susceptible to high uncertainty due to various methods used to estimate financial savings.
- The majority of plant operators reported an improvement in organic matter of the soil and plant nutrient uptake rate thanks to the use of digestate.
- Heat recovered from the CHP unit spanned from almost zero to 90 %.The proximity of the AD plant to a heat end user requiring process heat for

drying or cheese production determined the degree of heat recovery that could be achieved at the site. Locating new AD installations next to heat demands is going to be a crucial factor to dramatically improve profitability in a future scenario of free-subsidy AD.

- The estimated efficiencies of the eight biogas plants expressed in terms of degree of degradation of volatile solids ranged between 34 % and 78 %. As expected, the performance of AD depended on the characteristics of the feedstock mix. Mixes with higher fractions of manures featured lower efficiencies owing to their lower biodegradability.
- Data points representing BMP_{plant} vs. HRT and $VS_{\%}^{crop/waste}$ from the eight case studies were fitted with a non-linear fitting curve function in Matlab to estimate the four parameters of the kinetic equation in Table 6-9. Despite the small sample size of agricultural biogas plants used in this study, the calibrated kinetic model could be used for preliminary design of manure-based CSTR reactors. Further work is needed to increase the number of case studies and subsequently confidence in the estimated parameters.
- The Excel based calculator predicted Capex accurately with *RMSE* of 0.321 while it underperformed in the prediction of Opex and fertiliser savings with *RMSE* of 1.228 and 1.487. The latter derived from the analysis that accounted for the outlier of Case Study 6. The economic model tended to overestimate Capex and Opex for biogas throughputs lower than approximately 50 m^3 h^{-1} and underestimated them for higher biogas throughputs.
- There was a linear correlation between fertiliser savings predicted by the model and total N in the feedstock mix. The model outputs matched well with data from the case studies with *RMSE* of 1.487, if the outlier of Case Study 6 was included, or 0.509 if the outlier from the analysis was excluded.
- The model could predict heat parasitic load and electric parasitic load with *RMSE* of 0.455 and 0.467 respectively. Model outputs showed that heat parasitic load was dependent on the DS content in the feedstock mix. On

the other hand, no trend was detected between electric parasitic load and the total annual wet tonne of feedstock utilized.

7. Conclusions

A combination of datasets and methods have been applied to create an integrated biomass resources management tool that has been instrumental to investigate the available biomass potential from livestock waste and the extent of utilization of this potential in AD plants. The biomass resource management tool can be applied to answer research questions concerning the quantification and efficient use of these resources to serve various needs, for instance in this case renewable energy production and organic fertilizer management. This tool can also be used as basis for spatial analysis in order to evaluate scales of operation, feedstock mixture, and geographical availability of feedstocks.Approximately 30 million tonnes of manures and slurries are available for AD in England. The study shows that by the end of 2017 only about 5 % of this was actually being used in biogas plants in England. This demonstrates that the unused potential arising from this resource in the area is still enormous. Despite the fact that manure is the most abundant and widely available substrate for AD, the findings reinforce the common wisdom that this resource is overlooked and underutilized, and quantify the true potential.

AD of agri-bioresources such as manures and crops has significant potential to deliver renewable energy in the form of biogas. An additional 36M GJ year^{-1} of renewable energy could be generated as biogas if the unutilised 95 % of agri-biosolids was used as feedstock in AD systems. The economics of this opportunity can be enhanced if more heat is recovered from the CHP to meet local heat demand via drying of the cake for animal bedding, bagged fertilisers, drying of animal fodder silage, process heat and district heating. Despite the small contribution of AD to renewable energy production compared to solar and wind energy, it is essential to provide ecosystem services by recycling nutrients and reducing GHG emissions from agriculture.This study demonstrates how spatial analysis could help investigate the consequences of energy and environmental policies on the deployment of AD. Specifically the aim was to examine the implications of the introduction of policy targets on minimum livestock waste utilization in AD plants. In the region examined 40 additional AD plants with capacities ranging between 122 to 198 kW_{el} would be needed if the policy target of 25 % of total biomass potential from livestock waste ought to be treated via anaerobic digestion systems. This degree of deployment rises up to 131 if the target is set at 50 % with capacities ranging between circa 60 to 190 kW_{el}.

A questionnaire was designed to gather information from agricultural biogas plant operators on operational data with the aim to investigate challeges, costs and benefits of on-farm biogas production as well as to corroborate the Excel based biogas calculator. This tool can provide a guidance to evaluate the profitability of agricultural biogas plants. When coupled with the biomass resource management tool, it creates an integrated tool capable of estimating the economic sustainability of biogas production via AD of available agricultural bioresource solids, in relation to the scale of operation, feedstock mixture, and geographical availability of feedstocks Agricultural biogas plants in the region utilize cattle manure as the base component in the feedstock mixture. Small to medium scale plants are installed next to the cattle sheds with transportation of feedstocks and digestate generally within 5 km from the plant. This leads to closing the loop of nutrients within the farm boundaries and improving soil health and plant growth. Off-farm transportation of biomass is unavoidable at larger biogas installations.

Availability of land for digestate spreading, costs of feedstock supply and proximity to heat end users determine the attractivity of investments in biogas production. The degree of heat recovery from the CHP unit is limited by the availability of eligible end users in the proximity of the installations. Farmers are keen to explore opportunities to enhance heat recovery. However, they are discouraged by costs, permitting and efficiency of heat transport over long distances.

Fertiliser savings are linearly related to the total N in the influent. Case Study 6 represents an exemption owing to savings being calculated on the total N content in the digestate. The estimations provided are susceptible to high uncertainty due to various methods used to estimate financial savings. The majority of plant operators have reported an improvement in organic matter of the soil and plant nutrient uptake rate thanks to the use of digestate.The kinetics underlying the biogas calculator can be described by Equation 7-1.

$$BMP = \frac{HRT \times [0.48 \times VS\%_{manure} + 0.02 \times (1 - VS\%_{manure})] \times [195 \times VS\%_{manure} + 478 \times (1 - VS\%_{manure})]}{HRT \times [0.48 \times VS\%_{manure} + 0.02 \times (1 - VS\%_{manure})] + 1}$$

Equation 7-1

The first order kinetic parameter for cattle manure in Equation 7-1 exceeds values found in the literature which are between 0.1 and 0.2. Despite the first order kinetic parameter for crops being within the range of values reported in the literature, it might underestimate the actual value found in practice.

Despite the small sample size of agricultural biogas plants used in this study, the calibrated kinetic model can be used for preliminary design of manure-based CSTR reactors. Further work is needed to increase the number of case studies and subsequently confidence in the estimated parameters**.**The estimated efficiencies of the eight biogas plants expressed in terms of degree of degradation of volatile solids range between 34 % and 78 %. As expected, the performance of AD depends on the characteristics of the feedstock mix. Mixes with higher fractions of manures feature lower efficiencies owing to their lower biodegradability. These results confirm findings from other studies in the literature (FNR, 2010; Ruile *et al.*, 2015; Ahlberg-Eliasson *et al.*, 2017).The biogas calculator estimates *Capex*, *Opex*, fertiliser savings, *HPL* and *EPL* with *RMSE* being respectively 0.321, 1.228, 1.487 (including outlier of Case Study 6), 0.455 and 0.467. The model tends to overestimate Capex and Opex for *BHT* lower than 50 m^3 h^{-1} and underestimate costs for *BHT* higher than this threshold.

Predictions of *Capex*, *Opex*, fertiliser savings, are susceptible to high uncertainties owing to costs being case specific. This entails that almost every AD plant is unique because it serves different specific needs. Operational costs depend on feedstock costs, digestate disposal costs, parasitic load, rent and labour. Fertiliser savings are dependent on a variety of local factors including digestate properties, method and timing of spreading and type of soil and climate.

The model created in this work has been used to show that *HPL* is dependent on DS of the influent. Data points relative to the case studies does not seem to follow this trend consistently due to the uncertainty associated with data provided by the plant managers and operators. *EPL* ranges approximately between 5 % and 15 % with an average of circa 8 % across the case studies investigated. *EPL* seems to be independent from the size of the plant represented by the variable Q_{in}.

This research highlighted key aspects of agricultural waste treatment via anaerobic digestion that are going to be crucial to ensure the viability and sustainability of this technology in a future with AD free of subsidies. The cost of feedstocks, especially crop-based feedstocks, land availability for digestate spreading and the proximity of heat end users to the plant are critical factors that can determine the success of an AD project.

It is equally important to focus on the valorization of digestate to ensure that this fertilizer is turned into a standardised marketable product. Finally, sustainability should be the guiding principle when AD is incorporated in farming to make sure that this technology provides beneficial effects on crop production, for example as a result of double cropping, that create synergies and avoid conflicts with food and feed production.

7.1. Evaluation of the study and future work

Results refer to data collected from a limited sample composed of only eight case studies. The limited size of the sample affects the degree of confidence in the estimation of the four parameters of the kinetic model. Obviously a larger sample could have improved the accuracy in the estimation of the kinetics. However, this still had to be combined with more accurate primary data. Future work should expand the investigation to include more data points from additional case studies.

The methodological approach adopted in this study to collect primary data from biogas plant operators and managers relies on interviews and questionnaires that were filled in with the operator during the site visits. Responses on wet tonne per annum of feedstocks, electricity produced and consumed, heat produced and utilized and biogas production should be based on metered data from the previous year of operations. Operators provided the best estimate to the best of their knowledge for each one of these variables. A rigorous check on the data provided was not possible.

The information on the value of HRT relative to the Case Studies was not provided directly from the biogas plant operators. This value had to be estimated based on the total annual wet tonne of feedstock utilized and the volume of the primary digester. This approach did not take into account the dilution in the estimation of the HRT since this information was not provided and any attempt to infer it was likely to be susceptible to high uncertainty.

The estimation of BMP_o and BMP_{th} is based on literature data. A more rigorous approach would require sampling each feedstock used at each site to measure:

- DS
- VS
- Nutrient contents
- BMP_o from BMP tests

- C, N, H, O and S via elemental analysis of each sample to calculate the theoretical BMP_{th} according to Buswell equation

Future work might consider the possibility to set up a campaign of on-site measurements that would directly feed feedstock characterization.

This research has focussed exclusively on agricultural biogas plants utilizing a mix of cattle slurry and manure with crops, crop residues and other waste. Cattle manure is by far the most abundant type of manure in the region that has been the focus of this study. Therefore, the majority of agricultural plants utilizes this feedstock as a base component of the mix.

Pig slurry and poultry manure show different biochemical characteristics from cattle manure. Therefore, the study should be expanded to include also agricultural biogas plants utilizing respectively pig slurry or poultry manure as the base component of the feedstock mix. This would lead to the estimation of a new set of parameters for the kinetic model underlying the Excel based biogas calculator for each one of the main types of manures.

The estimation of the N mineralization potential was based on typical average values of RAN for different types of digestates, i.e. liquid, cake and whole digestate, found in the literature. This is a simple approach that could allow to compensate for the lack of modelling approaches in the literature describing the fate of inorganic N during AD. It also led to underestimating the actual fertilizer value of digestate because it did not take into account the prediction of how phosphates availability changes during anaerobic digestion.

N mineralization consists in the conversion of organic N into inorganic forms of N, such as ammonium, nitrites and nitrates. The opposite mechanism is named immobilization. The C/N ratio of the degradable organic fractions determines the balance between the two mechanisms. Low values of this ratio, for instance in slurries, leads to higher mineralization rates. Modelling this processes in anaerobic digestion is challenging, hence there are no models able to predict how available forms of nitrogen for plant uptake vary during AD in relation to residence time, temperature and initial content of total nitrogen.

Sustainability, as measured by LCA methodologies, was not included in the Excel-based evaluation tool developed in this study. Nowadays it is not possible to uncouple viability assessments from sustainability, which has become a critical decision making criteria. The implementation of an LCA was out of the scope of this research. Its implementation would have not been achievable within the project timeframe. However, it is important to include this aspect in future advancements of the tool.

This study investigated the implications of new environmental policies to enhance the degree of utilization of livestock via AD. The optimization problem set up to answer the research question was constrained by the maximum set distance of 5 km between potential plant locations and farms supplying feedstocks. However, this investigation did not tackle the issue whether a more distributed network of biogas plants was more efficient in terms of viability and sustainability than a more centralized network. This was not the objective of this research although it could the subject of further study.

Finally, in the future the biogas calculator could be developed further to consider other bioenergy technologies including LCA capabilities and turned into a comprehensive biomass resource management tool. This could entail the creation of an application developed in Python that can be interfaced with GIS to achieve a fully integrated biomass resources management tool.

A. Appendix: Sample questionnaire, case studies and datasets

A.1. Sample questionnaire

Water Informatics: Science & Engineering
EPSRC Centre for Doctoral Training

UNIVERSITY OF BATH

An insight into operations of agricultural biogas plants

Site Name:

Feedstock Mix						
Type	DS	tpa	Max. transportation distance (miles)	Feedstock Price (£ per tonne)	Gate Fee (£ per tonne)	Availability over the year

Please comment on any feedstock pre-treatments:

☐Maceration, ☐Steam explosion, ☐Other, please, specify:

Volume of the main digester or digesters:

Temperature (°C):

Digestate Storage			
Type	Volume (m^3)	Storage time (days)	Is biogas recovered?
☐Tank			Yes ☐ / No ☐
☐Lagoon			Yes ☐ / No ☐

Please comment on any digestate treatment post-storage:

☐Separation, ☐Drying, ☐Other, please specify:

Digestate management							
Type	tpa	Disposal Cost (£ per tonne)	Mean of transport	Maximum distance (mi)	Spreading method	Type of land	Time of the year
Whole							
Cake							
Liquor							

Are you able to approximately quantify the financial savings (£ per annum) on manufactured fertilisers thanks to digestate spreading?

Have you noticed any improvement in soil health and crop yields after digestate spreading compared to raw manures?

Biogas Production		
Throughput (m^3 per annum)	Methane content (%)	End use

☐CHP	☐Upgrading
Operating hours (hours per annum):	Upgrading technology:
Electricity production (kWh_e per annum):	Bio-methane end use:
Heat production (kWh_{th} per annum):	
Electricity parasitic load to meet plant energy demand as % of Electricity production:	
Heat parasitic load to meet digester heat demand as % of Heat production:	

Please specify end uses of heat recovered from the CHP, besides heat used for digester heating			
End use	Heat recovered (kWh_{th} per annum)	Energy source replaced (electricity, natural gas, kerosene or other)	Estimated savings (£ per annum)

Are you able to provide an approximate estimate of:

Total capital expenditure to build the plant (£):

Total operational expenditure (£ per annum):

A.2. Case Study 1: Kemble Farms

Feedstock mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cattle slurry	6	24,000	0	£0	£0
Maize	32	1,800	6	£36	N/A
Glycerol	2	182	300	£165	
Waste maize silage	32	640	0	£0	

Type of digestate	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Fibre	2000	£5,000	Tractor/ trailer	5	Injection	Arable	Mar-Oct
Liquor	26,000	£44,000	Umbilical/tanker	5	injection	Arable/ pasture	Mar-Oct

The farm houses 1,000 cows in total. However, they only collect the slurry produced from the barns where 650 dairy cows are housed all year round ensuring feedstock supply consistency throughout the year. They use sawdust as animal bedding material. Scrapers in the barns removes the slurry from the floor into a mixed concrete tank at the end of the barn. From here, it is pumped directly into the digester. Slurry does not contain impurities thanks to strict management practices in the barns. Rainwater, run-off from paved surfaces, leachate from the silage clamps and any spillages from the AD plant are collected.

They grow cereals, maize and grass on their land. The farm own approximately 2,500 acres of land. Maize and grass silages are primarily used to feed animals. Only a small fraction of it is wasted and fed to the digester. The silage is mixed with digestate, macerated and fed to the digester. Glycerol is a by-product of biofuel production, it is expensive hence they are gradually phasing it out.

The farm is a great example of closing the nutrient loop by using most of the waste streams arising from the dairy farm and recycling all digestate produced in the form of cake and liquor on farm land. They can leverage a better milk price, since the milk they produce comes from a farm implementing measures to enhance their sustainability. They have experienced an increase in milk yield. However, they are unsure if this increase can be attributable to the heating of water or to other factors.

The operator argues that the initial capital expenditure is the major obstacle to these kind of initiative. They are implementing other energy efficiency measures on farm such as replacing all lights with LEDs in the barns and installing more efficient ventilation systems. They raise concern about the future of their AD plant when subsidies end.

Operational and financial data:

- Digester volume: 1,400 m^3
- Temperature: circa 42 °C
- HRT: approximately 22 days
- OLR: roughly 5.2 kg VS m^{-3} day^{-1}
- Gas mixing system
- Air injection and ferric chloride addition for de-sulphurization
- Biogas throughput: approximately 1,200,000 m^3

- Methane content: 55 %
- *EPL*: 15 %
- *HPL*: 12 %
- CHP unit: 300KW_{el} with average run time of 8600 hours per annum.
- Excess heat used to heat water for the dairy cows and to provide heating for three households on farm.
- Digestate is separated into a liquid and solid fraction.
- After liquid-solid separation, the cake is stored on site in open-air heaps. The liquor is pumped into two open digestate tanks. From here the liquor is pumped into two lagoons at the edge of the fields to use in spring/summer as fertiliser. This provides circa 24,000 m^3 liquor storage capacity/
- Capex: £1.2 M (2008/9)
- Opex (Excl. labour, feed and depreciation): £80,000 - £100,000 per annum
- Heat from CHP replaces heating oil saving approximately £5,000 per annum.
- They estimate they have saved approximately £22,000 per annum on manufactured fertilisers thanks to digestate spreading.

A.3. Case Study 2: Keen's Cheddar Farm

Feedstock mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cow Slurry	6	10,000	0	Free	NA
Cheese whey	NA	1,238	0	NA	NA

Type of digestate	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Cake	2000	5	Agricultural	<1	Manure Spreaders	Grass or Cereal stubbles	Not Winter
Liquor	8000	3	Agricultural	<1	Umbilical or Tanker	Grass or Cereal stubbles	Not Winter

The AD plant has only two years of operations. It is an interesting Case Study of on farm small size AD plant mostly fed with cow slurry. The plant is adjacent to a barn where circa 250 dairy cows are housed all year round. Slurry drains from the barns to an open-air outdoor tank and from there it is pumped to the digester. The farm owns 500 acres of land. The site is well bounded within a concrete wall that prevent any leakage to an adjacent stream. Cheese production generates roughly 4.5 m^3 d^{-1} of wastewater for 250/300 days a year depending on demand. There is a day and night pattern in biogas production since cheese production is off at night. They have a 120 m^3 pre-digestion tank with occasional mixing.

The first two years of operations have been problematic due to poor design of the mixing system and internal heat exchanger. The mixing system was undersized and could not deliver the minimum power requirement. The initial design included only a central mixer that was unable to stir up the liquid in the digester leading to build-up of sediments by the digester walls. The digester quickly filled up with sediments and eventually failed. They had to shut down the digester for two months to open the cover, empty the digester, retrofit it with the installation of two mixers by the tank wall and a new internal heat exchanger.

The heat exchanger was initially installed by the tank walls. This caused the external sheeting of the thermal insulation to break up leading to leaks. The new heat exchanger has been installed far from the tank walls and raised from the tank floor by circa 1 meter.

They used chemicals to reduce sulphuric acid in the biogas but then they stopped dosing it last year. They blow air into the head space of the bioreactor to control sulphur concentration. The average concentration of sulphuric acid in the biogas is about 500 ppm but peaks of 1,000 have been measured. Activated carbon filters are before the CHP unit.

The payback time predicted at the feasibility stage was 5-6 years. However, the issues encountered in the first year of operations have lengthened the PBT to around 10 years. The farmer thinks that this is still an acceptable PBT for these types of investments and is happy with his decision.

They started looking at AD to treat cattle slurry and whey since 2010. They have always known that this organic material had good biogas potential. The main drive to build an AD plant was to become energy self-sufficient in the long term and less susceptible to the volatility of electricity and fossil fuel prices. They have also installed a PV plant of 80 kW.

Operational and financial data:

- Digester volume: 450 m^3

- Temperature: 38-42 °C
- *HRT:* approximately 21 days
- *OLR* has not been reported.
- The digester functions with a floating crust.
- Biogas throughput: approximately 200,000 m^3
- Methane content: 52 %
- *EPL*: 4 %
- *HPL*: 20 %.
- Two CHP units of 22 kW_{el} each with respectively 8,300 and 7,200 operating hours per annum and total efficiency of 81 %. One of the engines has lower operating hours because it is switched off at night for about 6 hours due to lower biogas production when cheese production is off.
- Excess heat is used to meet the demand for process heat in cheese production and to produce hot water for the dairy farm and farm household heating.
- The digestate can be pumped either directly to an uncovered tank or a dewatering unit.
- The liquor resulting from solids separation is temporarily stored in a separate tank then pumped to a lagoon by the fields for spreading. Total storage on site is about 6,000 m^3. The operator states that it would be too expensive to install a cover. It would also imply more effort regarding health and safety issues, maintenance and repair. After liquid-solid separation, the cake is stored on site in open-air heaps. The liquor is pumped into a lagoon.
- Capex: £200,000
- Opex (Excl. labour): £5,000 per annum for maintenance and repair
- Heat from the CHP replaces kerosene with approximate savings of £5,000 per annum.

- They have not noticed any fertiliser saving yet. It is still too early to notice any savings since they have been in operation for only two years.

A.4. Case Study 3: Y-farms, Downhead

Feedstock mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cow Slurry	10	13,000	0	0	NA
Waste maize silage	NA	1,100	0	NA	NA

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Whole	13,000	2.50	Tractor and trailer or umbilical	10	Dribble bar or spraying plate	Arable	All-year weather dependent

This is another interesting Case Study of a medium-large dairy farm adopting on farm AD to treat cattle slurry. Cattle slurry makes most of the feedstock mix with waste silage making the remaining part. Typically a dairy farm produce 5 % to 10 % of waste fodder silage. The operator estimates that for a dairy farm of 1,000 cows circa 12,000 tonne of fodder silage a year are needed, waste fodder silage amounts to roughly 1 tonne per cow per annum. This material is available to use directly into the AD plant at no cost.

The plant was commissioned in December 2014, the start-up lasted 3 months and since then has been running efficiently. The dairy farm houses 1800 cows in total, however only the slurry collected from two sheds adjacent to the AD plant, with roughly 700 cows housed all year round, is sent to the digester. The remaining slurry is not intercepted.

The slurry is scraped from the floor of the barns into a reception pit at the end of sheds. The bedding material is Envirobed™, which is recycled paper whereas in the other barn is sawdust. Bedding material from recycled paper is removed and stored in a heap outside. This material is not used in the AD plant. The slurry in excess overflows into the lagoon adjacent to the AD plant. The overflows arises because the AD plant has been design to treat an annual quantity of slurry equivalent to 600 dairy cows.

From the reception pit the slurry is pumped into the uncovered mixing tank of 115 m^3 where slurry is mixed with waste maize and grass silages. There is a small silage clamp next to plant where the waste maize and grass silages are stored. The operator hires a vehicle from the farm for loading.

The operations had to stop for two months since antibiotics used to treat the cows ended up in the slurry eventually killing the microorganisms in the digester. This demonstrates that the biology in the digester is very sensitive to the feed quality.

The operator used to work for the farm. In 2014 he started to investigate the opportunity to invest in AD to take advantage of the high FITs on electricity production. The farm owner did not want to invest in the venture, he was sceptical about the reliability of the technology and the uncertainty associated with it. Hence, the operator decided to carry on alone with the investment and rented out the land needed to build the plant.

The operator argues that had the farm owner decided to invest in AD, the investment would have been more profitable for several reasons:

- There would be no rent.

- The insurance would have costed a few hundred pounds compared to thousands of pounds as it would have been included in the farm insurance.
- They would have used spare labour in the farm at the same cost of a farm employee.
- They would have saved on the electricity bills rather than paying a fee of £ 0.06 per kWh for the electricity they get from the AD plant.

The farm owner now regrets that he did not invest at the time when the tariffs where advantageous. Under current government subsidies, it is unlikely that he would invest in AD.

There is no in line monitoring of the AD plant. Occasionally samples are taken to check biogas and digestate quality. The operator has a measuring device on site to monitor biogas quality and FOS/TAC. The operator used to take samples once a month and send them to an external lab for analysis. However, he has not seen any benefits from sampling digestate so frequently, hence now he does it once every four months approximately.

Operational and financial data:

- Digester volume: 1000 m^3
- Temperature: 40 - 45 °C
- *HRT*: 28 days
- *OLR*: 4 kg VS m^{-3} day^{-1}
- The digester functions with a floating crust.
- Biogas throughput: approximately 600,000 m^3
- Methane content: 51 %
- *EPL*: 6 %
- *HPL*: 40 %

- One CHP unit of approximately 125 kW_{el} with 38 % electrical efficiency, 48 % thermal efficiency, 8,580 operating hours per annum producing 1,000,000 kWh_{el} per annum.
- There is an air blower to control sulphur hydrogen concentration in biogas.
- A log dryer is located next to the CHP. The operator charges a fee for the service and he can also claim the RHIs. This ensures a revenue stream larger than combined revenues from FITs and RHIs for digester heating. Almost the entire excess heat from the CHP is utilized for log drying.
- From the digester digestate is pumped directly into a lagoon of about 8,000 m^3. Here it is mixed with slurry overflowing from the reception tank. On average 70-80 % of the volume of the lagoon comes from digestate.
- Capex: £900,000 (The capital expenditure for the construction of the biogas plant was £800,000 for the physical cost plus about £100,000 for other expenses)
- Opex (Excl. labour, feed and depreciation): £62,500 per annum
- Reported savings on manufactured fertilisers are approximately £5,000 per annum.
- The operator estimates that the plant requires roughly 400 hours per annum of operator time.

A.5. Case Study 4: Wyke Farms

Feedstock Mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cow Slurry	NA	58,084	1 (Pipeline)	0	NA
Cheese whey	20	17,674	1 (Pipeline)	£25	NA
Rape straw	93	1,224	~30 (Trucks)	£50	NA
De-lactose whey condensate	53	7,398	~300 (Ireland)	£52	NA
Effluent sludge from waste water treatment plant	5	5,618	1 (Pipeline)		NA
Maize silage	30-35	3,661	~35 (Trucks)	£40	NA
Apple pomace	22	3,105	6 (Trucks)	£10	NA
Process bread	65	7,029	~150 (Trucks)	£100	NA
Weevil infested wheat		136	NA	£90	
Wyke Farms' waste grass silage		787	<5	£5	
Additional whey permeate	6	80	~1	£6	
Wyke Farms' Farm cattle FYM	NA	175	~1	NA	
Factory waste (diverted waste water)	6	418	~1	NA	
Pig slurry	NA	9485	~1	NA	

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Whole	59,008	3	Tankers/ Tractors	NA	Spraying plate/ injection	Arable/ grassl and	March-October

This Case Study is representative of a large-scale biogas plant treating a wide range of feedstocks totalling circa 114,874 tonne per annum. Some organic materials are generated in-house at the dairy farm and cheese factory while others are by-products from the food industry with high biogas yields.

The feedstock mix used on site yields a high biogas throughput making biogas upgrading financially viable. The farm owns circa 1000 acres of land and 1000 dairy cows housed all year round. They do not charge any gate fee apart from when they occasionally receive waste from new suppliers. In this case, they charge low gate fees of around £6 per tonne.

Seasonality of feedstock availability does not have a significant impact on operations. Dairy cows are housed almost all year around apart from short spells in summer. Apple pomace is available only in late summer and autumn. Delactose whey concentrate is mostly available in spring and summer. The supply of the remaining feedstock is quite steady throughout the year.

There are no feedstock pre-treatments except from rape straw milling. Rape straw has no alternative use as bedding material and farmers need to dispose of it. A mixing tank of 500 m^3 is used as pre-digestion buffer tank for cheese whey with storage time lower than 5 days.

Operational and financial data:

- 4 tanks of 4,600 m^3 each.
- Temperature: 40 °C
- *HRT*: 45-55 days
- *OLR*: 4/5 kg VS m^{-3} day^{-1}.
- Total biogas throughput: approximately 13,894,000 m^3
- Methane content: 55 %
- *EPL*: 100 % (some electricity is imported from the grid to meet demand for biogas upgrading)
- *HPL*: circa 50 %

- Two CHPs of 499 kW_{el} power the plant and the farm. One CHP is installed on site whereas the other CHP is installed at the dairy farm. A biogas pipeline transports the biogas from the plant to the farm. Approximately 250 m^3 h^{-1} of biogas are fed to each CHP unit. The remaining biogas is sent to upgrading via membrane technology. Biogas is mixed with propane at between 3 and 4 % in volume to increase the LHV to 39 MJ m^{-3}, which is the quality standard required by the gas grid.
- Sulphur in biogas is kept below 200 ppm to minimize corrosion of the CHP engine via a combination of methods including ferric chloride, air injection and activated carbon filters.
- The operator estimates that the CHPs produces circa 8,505,954 kWh_{th} per annum each. All heat from the CHP on the AD site is used to heat the digesters. Circa 2,469,730 kWh_{th} per annum of heat is used to pre-heat boilers for the cheese factory.
- A storage tank of 4,600 m^3 has a storage capacity equivalent to 1-2 days of digestate production. This is possible thanks to several tankers or tractors that take digestate away on a daily basis. The remaining digestate is pumped to an open-air lagoon in the field close to the site. The lagoon will be covered to comply with environmental regulations.
- Capex: £16 M
- Opex (Excl. labour): not available

A.6. Case Study 5: Bromham farm house

Feedstock Mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Maize silage	30-40	30,000	~5 (90%)	£35	NA
Rye silage	38	3,105	~5	£35	NA

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Whole	40,000	3.50	Lorry (25 m^3)/ Tanker/ Tractor	~7	Umbilical/ dribble bar	Arable	March-October

This is a purpose grown crop only plant treating maize and rye silage. It is self-sufficient with regard to feedstock supply with approximately 5,000 acres of land owned or rented by the farm. They have two dairy units on farm, however they do not use any cattle slurry or manure because they do not trust the quality of the waste and its biogas yield is unpredictable.

The plant was commissioned in December 2017, hence it has just started operations. The site has not been fully developed yet since they still have to complete the construction of a Combi-bag of 6,000 m^3 that will ensure the increae of the overall HRT to approximately 50 days.

Feedstock seasonality does not have any impact on biogas production. The supply of silage is steady throughout the year. Crops are harvested in autumn, chopped to pieces smaller than 10 mm and stored in the silage clamp. A macerator mixes solids with liquid prior to feeding.

The operator reports they have had an issue with one digester not performing as expected. He suspects that this might be due to a batch of rye silage of poor quality that was fed to the digester, affecting the microbiology in the digester.

They also want to explore the option to recover carbon dioxide for drink manufactures. The operator estimates that they earn approximately £1 per cubic meter of biogas produced. The operator monitors the plant on a regular basis. They take samples 3-4 times a week to measure FOS/TAC and DS. Twice a month a sample is sent to NRM laboratories for a comprehensive analysis of the digestate. The operator checks the quality of the silage regularly.

Operational and financial data:

- 2 tanks of 4,000 m^3 each.
- Temperature: 41- 43 °C
- *HRT*: 30 days
- *OLR*: 4/5 kg VS m^{-3} day^{-1} (Estimated).
- Biogas throughput: approximately 7,884,000 m^3
- Methane content: 50 %
- EPL: 7 %
- HPL: 30 %
- Two CHPs of 499 kW_{el} each with approximately 8,500 operational hours per annum producing 3,800,000 kWh. Approximately 250 m^3 h^{-1} of biogas goes to the CHP unit. The remaining 650 m^3 h^{-1} of biogas goes to the upgrading via membrane technology to the gas grid.

- Excess heat is used to meet heating demand of the workshop, household, a garage and a swimming pool. They are exploring other possible options to use heat in excess such as in a greenhouse next to the plant.
- Ferric chloride is dosed to the digesters to reduce H_2S in combination with two activated carbon filters. Oxygen injection is present for redundancy.
- From a buffer storage tank of 300 m^3 post-digestion, a fraction of the digestate is pumped to two lagoons of 6,000 m^3 each whilst the remaining fraction is hauled to a 4,000 m^3 stainless steel tank 7 miles away from the plant. All storage tanks are uncovered apart from the buffer storage tank.
- They have installed a separator on site, which has not been commissioned yet. Once in operation, it will separate digestate into a solid and liquid fraction.
- Capex: £7.8 M
- Opex: £2.2 M per annum
- They have saved approximately £50,000 per annum on manufactured fertilisers thanks to digestate.

A.7. Case Study 6: Stowell farm

Feedstock Mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cattle slurry	6	55	0	£3.50	
Maize silage	30-40	14	0	£27.30	NA
Rye silage	38	6	0	£31.80	NA

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Cake	4,000	1.75	Tractor/ trailer	3.5	Spraying plate/ injection	Arable/ grassland	Arable land: March-October Grassland: 6 months between spring and summer
Liquid	20,000	3.50	Tanker/ umbilical	3.5		Arable/ grassland	

The farm houses roughly 470 dairy cows all year round. The feedstock mix is composed of dairy cow slurry, maize silage and rye silage. Most of the silage is produced on land owned by the farm. They started building the plant in 2011 and operations started in September 2012. The AD plant is adjacent to the dairy units. Water used from the dairy unit operations and rainwater are collected and mixed with cow manure. Slurry is pumped directly into the main digester. Silage is loaded into a solids feeder that moves the solids into a small tank where is mixed with liquid digestate. They have looked at potential markets for the solid fraction including:

- Producing bagged fertilisers.
- Drying to produce bedding material for the dairy unit.

In the first case, the economics does not stack up whereas in the second case hygiene regulations hinder the use of digestate as bedding material.

Operational and financial data:

- Digester volume: 2,500 m^3
- Temperature: 38-39 °C
- *HRT*: 40 days
- *OLR*: Not given
- Biogas throughput: approximately 2,400,000 m^3
- Methane content: 48-54 %
- *EPL*: 7 % (Personal communication with Andrew Barkas of EnviTec Biogas UK Ltd.)
- *HPL*: 22 % (Personal communication with Andrew Barkas of EnviTec Biogas UK Ltd.)
- A CHP of 499 kW_{el} operates approximately 8,565 hours per annum producing 4,200,000 kWh. The dairy farm consumes circa 18 % of total electricity production. The CHP was de-rated to 499 kW_{el} to get a better tariff.
- Reportedly, there is no activated carbon filter prior to the CHP. Sulphur is removed via air injection and ferrous chloride addition.
- Excess heat from the CHP is used for heating one household on farm. They have explored options to increase the amount of heat recovered but none of them stacked up.

- One covered storage tank of 5,500 m^3 without biogas recovery.
- The digestate is separated into a solid and liquid fraction.
- They send samples quarterly to external laboratory for a comprehensive analysis of digestate.
- Capex: £2.3 M
- Opex (Excl. labour, feed and depreciation): £234,683 per annum
- The operator claims that they can save up to approximately £100,000 per annum on manufactured fertilisers.

A.8. Case Study 7: Hunt family farm

Feedstock mix	DS	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cattle slurry	NA	10	0		NA
Cattle FYM	NA	10			NA
Poultry manure	NA	28	~6	£15	NA
Maize/Grass/Rye silage	NA	25	~8	£35	NA
Waste onions	NA	10	0		NA

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Whole	50-60	NA	Tankers	NA	Umbilical	Arable	March-October

The plant was commissioned in September 2013 and it was initially built with a total installed power of 500 kW_{el} to produce electricity and heat. The initial investment was £2,200,000 with additional costs to upgrade the plant in the following years with a new tank, another CHP unit of 500 kW_{el} and 6 boilers. The upgrading was necessary to increase the plant capacity to receive more waste. The plant design ensures redundancy thanks to two main digesters that work in parallel.

They used to operate a dairy unit that was shut down since it was not profitable anymore due to low milk prices. They use cattle slurry, cattle FYM and poultry manure in the feedstock mixture sourced from farms nearby. Feedstocks are mix in a pre-tank and then pumped into the main digester. The plant owner argues that AD is not viable is feedstocks have to be purchased.

Operational and financial data:

- 2 main digesters of 2,400 m^3 each.
- One storage tank of 4,500 m^3
- Temperature: 38 °C
- *HRT*: 90 days (Including residence time in secondary tank)

- *OLR*: Not given
- Biogas throughput: 3,922,410 m^3 (Estimated)
- Methane content : 52 %
- EPL: it has not been provided.
- HPL: 10 %
- Two CHPs of 499 kW_{el} operate approximately 90 % of the year.
- Excess heat is used to meet demand of drying paper sludge and maize silage to produce bedding for poultry. The company providing the paper sludge pays the plant owner in proportion to the amount of water removed from the sludge.
- From the secondary tank digestate is separated and then pumped to a lagoon of 24,000 m^3 capable of storing the sludge for 8 months.
- Capex: £2.2 M initial investment plus additional £600,000 for a tank and CHP.
- Opex (Excl. labour): 125,000 £ per annum including £85,000 of maintenance and £40,000 of other items.
- They have experienced considerable savings on chemical fertilisers equivalent to 100 tonnes of chemical N a year.

A.9. Case Study 8: Rushywood farm

Feedstock mix	DS (%FM)	Tonne per annum	Max. transportation distance (km)	Feedstock Price (£ per tonne)	Gate Fee
Cattle slurry	10	130	0	-	NA
Cattle FYM	30	50	0	-	NA
Waste silage	30-40	6	0	-	NA

Type	Tonne per annum	Disposal Cost (£ per annum)	Mean of transport	Max. distance (km)	Spreading method	Type of land	Time of the year
Cake	10	NA	Tractor and trailer	5	NA	Arable/ Grassland	All year round
Liquor	80	NA	Pumped to fields	-	NA	Arable/ Grassland	All year round

The AD plant is adjacent to the dairy farm housing roughly 2,000 cows all year round. Slurry is scraped from the barns and pumped to the reception pit at the biogas installation. They feed the AD plant only with waste or residues from the dairy farm including cattle slurry, FYM and waste animal fodder. They commissioned the plant in 2017 and started the operations in October 2017. A tank outside the AD plant collects wash water from the barns that contains sand, which is the bedding material for the cows. The sand is separated from the water in a sedimentation tank prior to the AD plant.

Operational and financial data:

- 1 double ring tank of circa 6,000 m^3
- Temperature: 39 °C
- *HRT*: 40 days
- *OLR*: Not given
- Biogas throughput: 1,927,200 m^3
- Methane content: 59 %
- *EPL*: 6 %
- *HPL*: 18 %
- Two CHPs of 360 and 126 kW_{el} operate approximately 8,131 and 8075 hours a year.
- Excess heat from the small CHP and heat produced in a boiler are used to dry animal fodder silage. A fraction of the heat from the big CHP is used to pre-heat the slurry in the reception tank.
- A storage buffer tank of 100 m^3 ensures one day worth of storage capacity. Digestate is then pumped to a separator and the liquor sent to a lagoon adjacent to the site for long term storage.
- Capex: Not available
- Opex: Not available

A.10. Operational data summary

Table A-1: Summary of main operational data collected from the eight case studies.

Case Study	Biogas End use	CHP (kWe)	Biogas throughput ($m^3\ y^{-1}$)	Biogas throughput ($m^3\ h^{-1}$)	Methane (%)	Volume of main digester (m^3)	HRT	Temperature	Electrical parasitic load (%)	Heat parasitic load (%)
1	CHP	300	1,200,000	137	0.55	1400	19	42	15	12
2	CHP	45	200,000	23	0.52	450	15	38-42	4	20
3	CHP	125	600,000	68	0.51	1000	25	40-45	6	40
4	CHP + Upgrading	1,000	13,894,769	1586	0.55	4600	58	40	100	50
5	CHP + Upgrading	500	7,884,000	900	0.5	4000	73	41.43	7	30
6	CHP	500	2,400,000	274	0.51	2500	33	38-39	7	22
7	CHP	1,500	4,227,858	483	0.52	2400	58	38	NA	10
8	CHP	486	1,927,200	220	0.59	6000	32	39	6	18

- HRT values are calculated as the ratio between the volume of the main digester and the total daily input flowrate in m^3 or wet tonne d^{-1}
- Biogas throughput for Case Study #7 has been estimated via standard BMP_o from Table A-3
- NA indicates that data are not available

A.11. Financial data summary

Table A-2: Summary of financial data that have been provided by biogas plant operators and managers

Case Study	Fertiliser savings	Capex £	Opex £ y^{-1}
1	£22,000	£1,200,000	£90,000
2	£0	£200,000	£5,000
3	£5,000	£900,000	£62,500
4	NA (2)	£16,000,000	NA (2)
5	£50,000	£7,800,000	£2,200,000
6	£99,715	£2,300,000	£234,683
7	£55,000	£2,800,000	£125,000
8	NA	NA	NA

- Capex for Case Study #7 has been estimated as the sum of £2.2 M of initial investment plus approximately £600,000 for an additional tank and CHP unit
- Financial data of Case Study #8 have not been provided

A.12. Waste characterization of the feedstocks utilized at the AD plants

The analysis focuses on agricultural biogas plants that co-digest cattle slurry and/or manure with crops, crop residues and other waste. Therefore, waste presented here only include those utilized at the eight AD plants examined. Table A-3 summarises data used to characterise feedstocks, references and assumptions.

Table A-3: Waste characterization of feedstocks utilised at the AD plants examined in this study. FM – Fresh Matter, DWC - Delactose Whey Concentrate, CWP – Cheese Whey Permeate, FYM – Farmyard Manure, CWW – Cheese Whey Wastewater, WWTP – Wastewater Treatment Plant

Feedstock	DS (% FM)	VS (% DS)	Total N (g L^{-1})	BMP_o (L CH_4 kg VS^{-1})	BMP_{th} (L CH_4 kg VS^{-1})	References
Cattle slurry	6.20	79.00	2.61	181	469	KTBL ; Møller *et al.* (2004); DEFRA (2010); Williams *et al.* (2016)
Cattle manure	26.40	84.00	6.70	209	469	KTBL ; Møller *et al.* (2004); DEFRA (2010); Williams *et al.* (2016)
Straw	90.50	96.00	5.9	195	432	Møller *et al.* (2004)
CWP	7.00	83.80	1.36	424	751	Labatut *et al.* (2011)
Maize silage	35.00	96.00	3.65	328	443	KTBL ; DEFRA (2010); Herrmann *et al.* (2016); Williams *et al.* (2016)
Rye silage	38.00	91.20	4.62	356	449	KTBL ; DEFRA (2010); Herrmann *et al.* (2016); Williams *et al.* (2016)
Grass silage	35.00	88.00	6.46	300	504	KTBL ; Buffiere *et al.* (2006); DEFRA (2010); Herrmann *et al.* (2016); Williams *et al.* (2016)
Poultry manure (Layer manure)	48.00	69.40	22.28	198	486	KTBL ; DEFRA (2010); Hidalgo *et al.* (2015)
Pig slurry	2.80	72.30	3.27	336	516	KTBL ; Møller *et al.* (2004); DEFRA (2010); Williams *et al.* (2016)
Winter wheat silage	35.00	92.00	5.74	301	447	KTBL ; DEFRA (2010); Herrmann *et al.* (2016); Williams *et al.* (2016)
Glycerol	84.00	94.70	0	751	929[3]	KTBL ; Astals *et al.* (2011)
Waste onions	23.70	91.50	6.64	400	494	Schievano *et al.* (2009); Lesteur *et al.* (2010)
Apple pomace	20.20	97.50	5.9	317	416	KTBL ; Buffiere *et al.* (2006)

[3] Values of BMP_0 and BMP_{th} for glycerol presented in Table A-3 are taken from respectively the work of Astals *et al.* (2008) and the online European feedstock atlas by KTBL.There is a discrepancy between these values and the theoretical BMP calculated according to Buswell equation. In fact, if a chemical formula of $C_3H_8O_3$ for glycerol is assumed the theoretical BMP according to Buswell would be 426 L of methane per kg of VS, which is much lower than the value reported in the literature.

Process bread	88.20	98.10	13.86	310	423	KTBL ; Tufvesson *et al.* (2013)
DWC (4) (5)	53.00	83.80	1.36	424	751	Labatut *et al.* (2011)
Sludge from CWW-WWTP (4) (6)	5.00	27.08	6	342	527	Hidalgo *et al.* (2015)
CWW (4) (5)	6.00	83.80	1.36	424	751	Labatut *et al.* (2011)

If not directly reported in the literature, theoretical BMP_{th} in Table A-3 can be calculated as follows:

- If COD and VS are reported in the paper referenced, then theoretical BMP_{th} equals 350 multiplied by the ratio COD/VS.
- If BMP_o and BD are reported in the paper, theoretical BMP_{th} is calculated as BMP_o/BD.
- If fractionation of VS is known, then theoretical BMP_{th} can be calculated via Buswell equation according to typical chemical formula for each fraction of VS, namely lipids, proteins, carbohydrates, crude fibres and VFAs, illustrated in Table A-4.

Table A-4: Fractionation of volatile solids to calculate the theoretical bio-methane potential according to Buswell equation. Fractionation and chemical formulae are based on Jensen *et al.* (2013).

VS Component	C	H	N	O	L STP CH_4 g VS^{-1}
Lipids	57	104	0	6	1.012
Proteins	5	7	1	2	0.495
Degradable carbohydrate	6	10	0	5	0.414
Non-degradable carbohydrate	6	10	0	5	0.414
Lignin	10	13	0	3	0.726
VFAs (As Acetate)	2	4	0	2	0.373

The biogas plant manager at Wyke Farms AD plant has provided a value for DS of 20 % for cheese whey utilised on site as well as DS for DWC, CWW and Sludge from CWW-WWTP. Values of DS for maize, rye, grass and winter wheat silage have been directly provided by biogas plant operators. No information has been given on VS and BMPs for DWC, CWW and CWW-WWTP. It is assumed that DWC and CWW have the same properties as CWP while CWW-WWTP has the same properties as sewage sludge from WWTP.

A.13. Fertiliser value of manures, slurries and digestate

Defra fertiliser manual (DEFRA, 2010) and its latest update (Williams *et al.*, 2016) are the main source of information for typical average values for nutrients content of organic fertilisers and digestates in terms of NPK illustrated in Table A-5 and Table A-6.

Table A-5: NPK contents of different types of slurries and manures (Williams *et al.*, 2016) and financial value of each type of fertiliser based on fertiliser prices in Table A-7 and fractions of phosphate and potash available to plant uptake.

Organic fertiliser	DS (%FM)	Total N (g L^{-1})	RAN (g L^{-1})	Phosphate (g L^{-1})	Potash (g L^{-1})	Fertiliser value (£ t^{-3})
Cattle Slurry	6.2	2.61	1.06	1.06	2.61	£1.88
Cattle Manure	26.4	6.70	0.60	3.40	9.40	£5.06
Pig Slurry	2.8	3.27	2.28	1.05	2.00	£2.31
Pig Manure	24.0	7.70	0.80	5.70	7.40	£5.23
Layer Manure (Poultry)	48.0	22.28	8.38	14.18	16.88	£15.95
Litter Manure (Poultry)	57.0	26.42	9.10	16.16	19.58	£18.05
Sheep Manure	28.3	6.50	0.50	4.70	14.10	£7.22
Horse Manure	22.5	4.60	0.50	4.90	5.50	£4.07
Goats Manure	43.1	9.50	0.50	4.50	12.20	£6.44

Table A-6: Fertiliser value calculated for digestate based on fertiliser prices in Table A-7 (Williams et al., 2016) and fractions of phosphate and potash available to plant uptake.

Type of farm based digestate	DS (%)	Total N ($g\ L^{-1}$)	RAN ($g\ L^{-1}$)	Phosphate ($g\ L^{-1}$)	Potash ($g\ L^{-1}$)	Fertiliser value (£ t^{-1})
Whole	5.6	3.60	2.30	1.70	4.40	£3.62
Separated Liquor	3.0	1.90	1.30	0.60	2.50	£1.90
Separated Fibre	24.0	5.60	1.20	4.70	6.00	£4.84

Table A-7 shows prices of N, P and K based on market prices in 2018. These prices are subject to fluctuations throughout the year and changes from one year to another.

Table A-7: Fertilisers prices in 2018 (Graham Redman, 2018)

Fertiliser type	Prices (£ kg^{-1})	Standard fertilisers
Nitrogen	£0.55	Ammonium nitrate (34.5 % N)
Phosphate	£0.59	Phosphate-TSP (46 % P_2O_5)
Potash	£0.42	Muriate of Potash-MOP (60 % K_2O)

B. Appendix: List of technology suppliers and biogas plants managers

The author is grateful to all the companies that have provided information and quotations of their products. Specifically, the author would like to acknowledge the following companies, grouped together by type of main equipment:

- Tanks: Kirk Environmental Ltd and Balmoral Tanks Ltd.
- CHP, boilers, biogas clean-up, flare stack: Quantum ES gas engines, GEN-C Ltd and 2G-Energy Ltd.
- Biogas upgrading: Greenlane Biogas Europe Ltd.
- Screw press and centrifuge: Alfa Laval Ltd.
- Digestate belt drying: Alvan Blanch Development Company Ltd.
- Heat exchanger: HRS Heat Exchangers Ltd
- Mixers: Landia UK Ltd. and Xylem water solutions.
- Silage clamps: ACP (Concrete) Ltd
- Solids feeding systems: Pumpe GmbH

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- Roddy Stanning of RZ Energy Ltd

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- Andy Mercer of Bromham House Farm
- Gavin Davies of Stowell Farms
- The owner of Plusterwine House/Hunt Family
- Stuart Sherrin and Mark Voss of Ixora Energy Ltd.

C. Data used to quantify biomass resource potentials

Table C-1: Values used in Equation 3-1 to calculate the total biomass potential for different livestock groups according to the assumptions presented in (ADAS, 2008).

Livestock group	Sub-group	Excreta production (kg or L head^{-1} day^{-1})	Time spent in house	Fraction stored as slurry	Fraction stored as FYM
Cattle	Dairy breeding herd	53.00	62%	55%	23%
	Beef breeding herd	45.00	38%	14%	57%
	Dairy female over 2 years old (no offspring)	40.00	35%	15%	57%
	Beef female over 2 years old (no offspring)	32.00	38%	14%	57%
	Dairy female between 1 and 2 years old	40.00	35%	15%	57%
	Beef female between 1 and 2 years old	26.00	38%	14%	57%
	Dairy female under 1 years old	20.00	35%	15%	57%
	Beef female under 1 years old	26.00	38%	14%	57%
	Male over 2 years old	26.00	38%	14%	57%
	Male under 2 years old	26.00	38%	14%	57%
Pigs	Sows in pig	10.90	64%	55%	17%
	Gilts in pig	10.90	64%	55%	17%
	Other sows	10.90	64%	55%	17%
	Boars for service	8.70	72%	0%	69%
	Gilts not yet in pig	5.60	72%	55%	17%
	Pigs between 110 kg and over	5.10	100%	26%	45%
	Pigs between 80 kg and under 110 kg	5.10	100%	26%	45%
	Pigs between 50 kg and under 80 kg	3.70	100%	26%	45%
	Pigs 20 kg and under 50 kg	3.70	100%	26%	45%
	Pigs under 20 kg	1.30	100%	26%	45%
Sheep	Female breeding flock	4.20	5%	0%	100%
	Rams	4.20	5%	0%	100%
	Lambs under 1 years old	1.80	5%	0%	100%
	Other sheep over 1 year old	1.80	5%	0%	100%
Poultry	Pullets	0.04	100%	0%	50%
	Birds laying flock	0.12	100%	0%	50%
	Breeding flock	0.12	100%	0%	50%
	Broilers table chicken	0.06	100%	0%	33%
	Ducks	0.10	100%	0%	50%
	Turkeys	0.14	100%	0%	33%
Horses	Horses	24.50	25%	0%	100%
Goats	Goats	3.50	5%	0%	100%

D. Model outputs to compare with data from case studies

Case Study	DS (% wet weight)	VS (% wet weight)	Biogas throughput ($m^3\ h^{-1}$)	HRT (day)	V_{tank} (m^3)	HPL (%)	EPL (%)	Capex	Opex	W_{CHP}	Fertiliser savings
1	9.37%	8.04%	122	19	1459	30.00	12.00	£1,082,484	£47,133	268	£17,761
2	6.28%	5.00%	23	15	481	68.00	10.00	£473,516	£20,302	51	£6,634
3	8.36%	7.05%	57	25	1053	37.00	21.00	£799,032	£34,619	124	£9,638
6	14.12%	12.64%	242	33	2629	16.00	7.00	£1,655,467	£70,180	531	£22,360
7	33.52%	27.23%	633	58	9834	8.00	4.00	£2,695,304	£133,018	1388	£55,823
8	12.56%	10.47%	309	32	6265	31.00	10.00	£2,073,603	£85,635	678	£52,925

- Model outputs of Case Study #8 relative to Capex, Opex and Fertiliser savings could not be used for comparison since financial data were not provided by plant managers.

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